CUK-H03360-5-[illegible]

AMERICAN JOURNAL OF SCIENCE

ESTABLISHED IN 1818 BY
BENJAMIN SILLIMAN

.051
.001

EDITORS
RICHARD S. LULL · EDWARD S. DANA

ASSOCIATE EDITORS
REGINALD A. DALY · CHARLES PALACHE
CAMBRIDGE, MASS.

CHARLES SCHUCHERT · WESLEY R. COE
ALAN T. WATERMAN · HARRY W. FOOTE
ADOLPH KNOPF · · · · RICHARD FLINT
GEORGE E. NICHOLS
NEW HAVEN, CONN.

EDWARD W. BERRY
BALTIMORE

WILLIAM BOWIE · ARTHUR L. DAY
D. F. HEWETT
WASHINGTON

5

FIFTH SERIES

VOL. XXIX—[WHOLE NUMBER CCXXIX].

NEW HAVEN, CONNECTICUT
1935

CONTENTS TO VOLUME XXIX.

Number 169.

Structures and Phylogeny of Actinoceroid Cephalopods...*Curt Teichert* 1
Tertiary Grasses and Prairie Vegetation, High Plains, North America..............................*Maxim K. Elias* 24
Yale Fossils of Anthropoid Apes..............................*Aleš Hrdlička* 34
Glacial and Interglacial Development, Chittenango Falls State Park, Central New York..........................*Chauncey D. Holmes* 41
Oligorhynchia, A New Ordovician (Chazy) Brachiopod *G. Arthur Cooper* 48
A Middle Eocene Mammal, British Columbia..........*Loris S. Russell* 54

DISCUSSION AND COMMUNICATION.

Pegmatite Minerals in Marble, Falls Village, Connecticut, *William Agar* 56

SCIENTIFIC INTELLIGENCE.

CHEMISTRY AND PHYSICS.

An Introduction to Quantum Theory, by G. Temple........................*Leigh Page* 58
Hydrogen and Oxygen, by C. N. Hinshelwood and A. T. Williamson,...*J. E. Vance* 58
Chemical Results, German Deep-Sea Expedition 1925-27.......*Thomas G. Thompson* 59
Practice of Absorption Spectrophotometry, by F. Twyman and C. B. Allsop *W. W. Watson* 61
The World Around Us, by S. R. Powers, E. F. Neuner and H. B. Bruner; 61
Vorträge der Deutschen Physikalischen Gesellschaft; 62
Ergebnisse der Exakten Naturwissenschaften; 62
The Mystery of the Atom, by H. A. Wilson; 62
College Physical Science, by P. McCorkle and J. A. Lewis; 63
Colour Science, by W. Ostwald..................................*A. T. Waterman* 63

GEOLOGY AND MINERALOGY.

Traité de Géodésie, by P. Tardi..................................*Walter D. Lambert* 63
Geology, Country between Springs and Bethal, by F. A. Venter; 64
Carte Géologique de l'Angola, by F. Mouta and H. O'Donnell; 64
Tertiary Faunas, by A. M. Davies..............................*C. O. Dunbar* 65
Internal Structure of Mesozoic Brachiopoda, by H. M. Muir-Wood; 65
Les Brachiopodes du Dinantien de la Belgique, by F. Demanet; 66
The Cambrian Area, Rushton, by E. S. Cobbold and R. W. Pocock *Charles Schuchert* 66
Problems of Petroleum Geology, by W. E. Weather and F. H. Lahee, *Adolph Knopf* 67
Historical Geology, by W. A. Ver Wiebe; 67
Laboratory Manual, Physical and Historical Geology, by K. F. Mather and C. J. Roy...*R. F. Flint* 68
United States Bureau of Mines.. 68

MISCELLANEOUS SCIENTIFIC INTELLIGENCE.

Building, Roman Aqueducts, by E. B. Van Deman..................*Paul V. C. Baur* 69
The Myxomycetes, by T. H. MacBride and G. W. Martin................*J. S. Boyce* 70
Textbook of Histology, by A. A. Maximow and W. Bloom..............*R. T. Hill* 71
High Gods, North America, by W. Schmidt..............................*J. C. Archer* 72
American School of Prehistoric Research by G. G. MacCurdy..........*E. A. Hooton* 72
Diametral Changes in Tree Trunks, by F. W. Haasis...................*C. G. Deuber* 74
Streifzüge durch die Umwelten von Tieren und Menschen, by J. v. Uexküll and G. Kriszat; 74
Papers from the Tortugas Laboratory, Carnegie Institution, Washington; 74
Studies Protozoan Parasites of Fishes, Illinois, by R. R. Kudo 75
Animalium Cavernarum Catalogus, by Benno Wolf..... ....*W. R. Coe* 75
Palaeolithic Human Industries, Northwest Punjab and Kashmir, by J. Hawkes, C. Hawkes, and H. de Terra..............................*G. G. MacCurdy* 75
Applied Acoustics, by H. F. Olsen and F. Massa..........................*H. M. Turner* 76
Forty-eighth Annual Report of Bureau of Ethnology 1930-31; 76
Les Lois Fundamentales et de Electricité, by L. Bouthillon and M. Goudonnet; 76
Observatory Publications; 77
Palaohistologie der Pflanze, by Elise Hofmann....................... ....*H. Castle* 77
Fog, by Alexander McAdie........................... ....*Frank Schlesinger* 78

Obituaries 79

Publications Recently Received.. 79

Number 170.

Is The "Roots-Of-Mountains" Concept Dead? *Chester R. Longwell* 81

Hypothyridina Venustula (Hall) in Pennsylvania *Bradford Willard* 93

Basal Relations of Galena Dolomite, Upper Mississippi Valley, Lead and Zinc District *G. Marshall Kay and Gordon I. Atwater* 98

Flaws and Tear Faults .... *Elwyn L. Perry* 112

Miocene and Pliocene Mammalian Faunas, Valentine, Nebraska .... *R. A. Stirton and Paul O. McGrew* 125

What is "Pocono"? .... *George Halcott Chadwick* 133

Structural Detail Near Western Border of Thrust Sheets, North of Shoshone River, Wyoming *Martin M. Sheets* 144

The System, $MgO\text{-}FeO\text{-}SiO_2$ *N. L. Bowen and J. F. Schairer* 151

SCIENTIFIC INTELLIGENCE.

PHYSICS

The Thermodynamics of Electrical Phenomena in Metals, by P. W. Bridgman; 218

The National Physical Laboratory—Report 1933..... *A. T. Waterman* 218

GEOLOGY

Glacial Deposits Outside Wisconsin Terminal Moraine, Pennsylvania, by F. Leverett .... *R. F. Flint* 220

Outline of Physical Geology, by C. R. Longwell, Adolph Knopf and R. F. Flint .... *Marland Billings* 220

MISCELLANEOUS SCIENTIFIC INTELLIGENCE

Chan Kom: A Maya Village, by R. Redfield and A. Villa *Alfred M. Tozzer* 222

Ventilation: A Textbook for Students and Engineers, by E. L. Joselin *L. E. Seeley* 222

Zur Erforschung des Weltalls, Acht Vorträge über Probleme der Astronomie und Astrophysik, by P. ten Bruggencate, E. F. Freundlich, et al; 223

Earth, Radio and the Stars, by H. T. Stetson ...... *Frank Schlesinger* 223

Obituaries 224

Number 171.

Keratophyres, Eastern Oregon, Spilite Problem, Part I *James Gilluly* 225
The Period of Radium......*Ellen Gleditsch and Ernst Föyn* 253
Study of System Lime-Potash-Alumina *L. T. Brownmiller* 260
Pre-Cambrian Granites of the Black Hills *Garvin L. Taylor* 278
Fossils, Marine Pleistocene Terraces, San Pedro Hills, California....................*W. P. Woodring* 292

SCIENTIFIC INTELLIGENCE.

CHEMISTRY

Fundamentals of Chemical Thermodynamics, by J. A. V. Butler *Blair Saxton* 306

GEOLOGY

Changing World of the Ice Age, by Reginald Aldworth Daly *Richard Foster Flint* 306
Useful Aspects of Geology, by S. J. Shand.............*Adolph Knopf* 309

MISCELLANEOUS SCIENTIFIC INTELLIGENCE

The Great Design: Order and Intelligence in Nature, by Frances Mason...*Henshaw Ward* 309
General Astronomy, by H. Spencer Jones...........*Frank Schlesinger* 310
Report of the Science Advisory Board of July 31, 1933, and May 28, 1934 310

Obituaries 311

Publications Recently Received 312

Number 172.

Stream Carved Slopes and Plains, Desert Mountains *Ross Field* 313

The Ostracoderm Genus Dartmuthia Patten *George M. Robertson* 323

Keratophyres of Eastern Oregon and the Spilite Problem, Part II .... *James Gilluly* 336

Arkose Deposits in the Humid Tropics, Study of Sedimentation, Southern Mexico .... *Paul D. Krynine* 353

Striated Rock Surfaces, St. Francois River Valley *Chester K. Wentworth* 364

The Origin of Potash-Rich Rocks .. *Ruth Doggett Terzaghi* 369

DISCUSSION AND COMMUNICATION.

Climates of the Pleistocene: A Review *Richard Foster Flint* 381

SCIENTIFIC INTELLIGENCE.

CHEMISTRY AND PHYSICS

The Spirit of Chemistry, by A. Findlay .... *John A. Timm* 386

Kleiner Grundriss der Theoretischen Physik, by A. Haas ... *Leigh Page* 386

GEOLOGY AND MINERALOGY

Geology of Parts of Southern Norway, by O. Holtedahl, A. Bugge, et al.; 386

Studien über Lamellibranchiaten des Leptaenakalkes in Dalarna, by Orvar Isberg .... *Charles Schuchert* 387

Report of First Scientific Expedition to Manchoukuo, under leadership of Dr. Shigeyasu Tokunaga 388

Getting Acquainted with Minerals, by G. L. English....... *W. E. Ford* 388

MISCELLANEOUS SCIENTIFIC INTELLIGENCE

Researches on Fungi, by A. H. Reginald Buller .... *J. S. Boyce* 389

Modes of Behavioral Adaptation in Chimpanzee to Multiple Choice Problems, by Robert M. Yerkes .... *W. R. Coe* 389

Food and Health, by Henry C. Sherman; 389

Lexique Technique Anglais-Francais, by Guy Malgorn 390

OBITUARY

David White.. *E. W. Berry* 390

Obituaries.. 391

Publications Recently Received.................................. 392

Number 173.

A Statistical Method for Comparison of Heavy Mineral Suites .... *Lincoln Dryden* 393

Interpretation of Mineral Facies in Metamorphic Rocks *F. J. Turner* 409

Layered Peridotitic Laccoliths, Trout River Area, Newfoundland .... *Earl Ingerson* 422

Radium Content, Lavas, Lassen Volcanic National Park, California .... *Robley D. Evans and Howel Williams* 441

Oeselaspis, A New Genus of Ostracoderm *George M. Robertson* 453

DISCUSSION AND COMMUNICATIONS.

Paleozoic Plankton of North America ... *Charles Schuchert* 464

SCIENTIFIC INTELLIGENCE.

CHEMISTRY AND PHYSICS

Chemical Kinetics and Chain Reactions, by N. Semenoff.. *G. C. Akerlof* 465

Soil Analysis: A Handbook of Physical and Chemical Methods, by C. H. Wright .... *M. F. Morgan* 466

GEOLOGY AND MINERALOGY

Guide to the Geological Model of Ardnamurchan, by J. E. Richey *Adolph Knopf* 466

Geography and Geology of the Region Including Cape Cod, the Elizabeth Islands, Nantucket, Marthas Vineyard, No Mans Land and Block Island, by J. B. Woodworth and Edward Wigglesworth .... *R. F. Flint* 467

Molecule e Cristalli, by E. Fermi .... *W. E. Ford* 467

MISCELLANEOUS SCIENTIFIC INTELLIGENCE

The Scientific Basis of Evolution, by T. H. Morgan; 468
The Philosophy of a Biologist, by J. S. Haldane; 468
Antonio Rodolico (1911-1932), Ricerche di Biologia .... *W. R. Coe* 468

The Science of Rubber, by R. F. Dunbrook and V. N. Morris *Harry L. Fisher* 468

Through Space and Time, by Sir James Jeans .... *Frank Schlesinger* 470

Sex and Culture, by J. D. Unwin .... *Edward S. Robinson* 470

The Human Body, Its Structure and Activities and the Conditions of Its Healthy Working, by H. Newell Martin .... *H. E. Himwich* 471

Obituaries 471

Publications Recently Received 472

Number 174.

Mylonites from San Andreas Fault Zone *A. C. Waters and C. D. Campbell* 473
Tectonic Disturbances connected with Plutonic Bodies, Oslo Region .... *Olaf Holtedahl* 504
Rhomboid Ripple Mark .... *A. O. Woodford* 518
Semionotus cf. Gigas, From Triassic of Zion Park, Utah, *Curtis J. Hesse* 526

SCIENTIFIC INTELLIGENCE.

CHEMISTRY AND PHYSICS

Crystals and the Polarising Microscope, by N. H. Hartshorne and A. Stuart .... *J. F. Schairer* 532
Carbohydrates, by E. F. Armstrong and K. F. Armstrong *R. D. Coghill* 532
Electrolytes, by Hans Falkenhagen .... *H. S. Harned* 533
From Galileo to Cosmic Rays, by Harvey Brace Lemon *A. T. Waterman* 534

GEOLOGY

Kyanite and Vermiculite Deposits of Georgia, by Louis M. Prindle *Henry Hotchkiss* 535
Navy-Princeton Gravity Expedition to West Indies, 1932; 535
Géologie Appliquée, by E. Raguin .... *C. R. Longwell* 536
Bibliographic Index of Paleozoic Ostracoda, by R. S. Bassler and Betty Kellett .... *Charles Schuchert* 537
The Mesozoic Paleontology, British Somaliland, by W. A. Macfayden, et al. .... *C. O. Dunbar* 537

MISCELLANEOUS SCIENTIFIC INTELLIGENCE

Subsidence within the Atmosphere, by Jerome Namias ... *C. L. Mitchell* 538
Publications of the Royal Astronomical Society........................ 538
Scientific Survey of Porto Rico and the Virgin Islands, by Herbert Osborn .... *R. B. Friend* 538
Planetario Tascabile Hoepli, by G. L. Andrissi and A. Tosi *U. Ranieri* 539
Biology for Everyman, by J. A. Thomson 539
A Manual of the Common Invertebrate Animals, by H. S. Pratt *W. R. Coe* 540

OBITUARY

Michael Idvorsky Pupin .... *Charles F. Scott* 540
Obituaries 542
Publications Recently Received 543
Index To Volume XXIX 545
Contents, Volume XXIX

CALCUTTA UNIV
Sec. No.........
Book No.........
LIBRARY

AMERICAN JOURNAL OF SCIENCE

JANUARY 1935

STRUCTURES AND PHYLOGENY OF ACTINOCEROID CEPHALOPODS.

CURT TEICHERT.

INTRODUCTION.

The following pages are mainly devoted to a résumé of the results of former studies of the present writer, which recently have been published in German (1933). These results were reached by observations on North American and Canadian actinoceroid cephalopods. Still more recently (1934) additional facts have been uncovered by a study of actinoceroids from North Greenland. The chapter on phylogeny, however, is original.

NOMENCLATURE.

Part of the nomenclature pertaining to the Actinoceroids has been compiled and redefined by Foerste and Teichert in 1930. As the study of the actinoceroid structures advanced it became necessary to introduce a number of new terms designating so far unknown, insufficiently known, or disregarded facts and features of the representatives of this group.

Already Foerste and Teichert proposed to call the outwardly curved part of the septal neck the *brim*. The area of contact between the lower surface of the connecting ring and the immediately underlying septum was called the *adnation area*, whereas the part of the connecting ring which is free from contact with the upper as well as with the lower septum was called the *free part of the connecting ring*. Below are listed terms designating new features which have been discovered or extensively described by the present writer, in his detailed study of the actinoceroid structures. For further explanation the reader is referred to the following pages and still more to the original paper (1933).

Sec. No. ....
Book No. ....
LIBRARY

AMERICAN JOURNAL OF SCIENCE

JANUARY 1935

STRUCTURES AND PHYLOGENY OF ACTINOCEROID CEPHALOPODS.

CURT TEICHERT.

INTRODUCTION.

The following pages are mainly devoted to a résumé of the results of former studies of the present writer, which recently have been published in German (1933). These results were reached by observations on North American and Canadian actinoceroid cephalopods. Still more recently (1934) additional facts have been uncovered by a study of actinoceroids from North Greenland. The chapter on phylogeny, however, is original.

NOMENCLATURE.

Part of the nomenclature pertaining to the Actinoceroids has been compiled and redefined by Foerste and Teichert in 1930. As the study of the actinoceroid structures advanced it became necessary to introduce a number of new terms designating so far unknown, insufficiently known, or disregarded facts and features of the representatives of this group.

Already Foerste and Teichert proposed to call the outwardly curved part of the septal neck the *brim*. The area of contact between the lower surface of the connecting ring and the immediately underlying septum was called the *adnation area*, whereas the part of the connecting ring which is free from contact with the upper as well as with the lower septum was called the *free part of the connecting ring*. Below are listed terms designating new features which have been discovered or extensively described by the present writer, in his detailed study of the actinoceroid structures. For further explanation the reader is referred to the following pages and still more to the original paper (1933).

AM. JOUR. SC.—FIFTH SERIES, VOL. XXIX, NO. 169, JANUARY, 1935.

Contact layer (Kontaktschicht): a deposit, occasionally formed between the connecting ring and the septum, preventing an immediate contact of both.

False contact of the connecting ring is present, if there is a contact layer between the connecting ring and the septum.

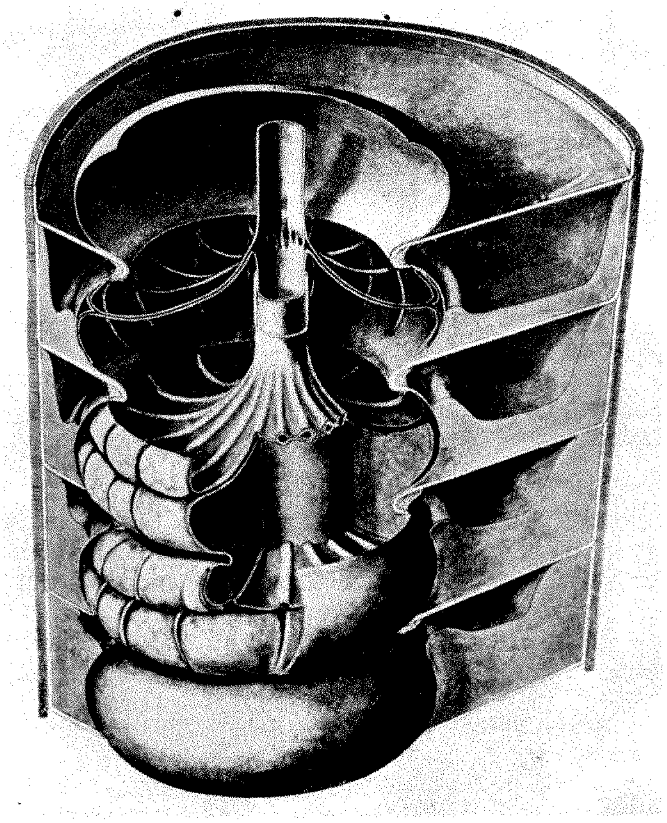


Fig. 1. Reconstruction of an Actinoceratoid shell of the type of *Actinoceras ruedemanni.*

Central obstruction deposits, mostly called "obstruction rings": solid deposits within the siphuncle (with the exception of the perispatial deposits).

Centrifugal type of obstruction rings: deposits first tending to fill out the marginal parts of the siphuncular segments.

- *Actinoceratidae* Hyatt
  - *Actinoceras* Bronn
  - *Kochoceras* Troedsson
  - *Maruyamaceras* Kobayashi
  - *Paractinoceras* Hyatt
  - *Rayonnoceras* Croneis
  - *Saffordoceras* Foerste and Teichert
  - *Troostoceras* Foerste and Teichert
- *Armenoceratidae* Troedsson
  - *Armenoceras* Foerste
  - *Cyrtonybyoceras* Teichert
  - *Elrodoceras* Foerste
  - *Megadiscosorus* Foerste
  - *Nybyoceras* Troedsson
  - *Selkirkoceras* Foerste
- *Huroniidae* Foerste and Teichert
  - *Huronia* Bigsby
  - *Huroniella* Foerste
  - *Discoactinoceras* Kobayashi
- *Gonioceratidae* Foerste and Teichert
  - *Gonioceras* Hall
  - *Lambeoceras* Foerste
- *Sactoceratidae* Troedsson
  - *Cyrtactonoceras* Hyatt
  - *Deiroceras* Hyatt
  - *Ormoceras* Stokes
  - *Sactoceras* Hyatt
- *Westonoceratidae* Teichert
  - *Westonoceras* Foerste
  - *Teichertoceras* Foerste
  - *Calhounoceras* Troedsson (of doubtful position)

This classification is certainly not to be regarded as final, but it is based on our present knowledge and may moreover contribute towards an understanding of the phylogeny of the Actinoceroids. Particularly the family *Sactoceratidae* needs further research, as also the family *Huroniidae* does.

SHELL MORPHOLOGY.

THE SIPHUNCLE.

a. *The Connecting Ring.*

As is well known the ectosiphuncle of ellipochoanitic cephalopods consists of the septal necks and of the connecting rings between the septal necks. The connecting ring attaches itself at the end of the brim and approaches the next following septum in a varying distance from the septal neck, sometimes in contact with the septum around the septal foramen along an adnation surface as defined by Foerste and Teichert in 1930. It follows the entire septal neck, gradually thinning out towards the outer edge of the brim, where the new connecting ring begins. With regard to the nature of the connecting ring two features are of importance: 1, the connecting ring is in most cases considerably thinner than the septum, 2, the connecting ring is made up of a material different from that of the septum. It is reasonable to assume that the connecting ring of the actinoceroids consisted of a material similar to that of the connecting ring of the living *Nautilus*.

We may speak of an *upper adnation surface* and a *lower adnation surface,* when the septum is in contact with the upper or the lower septum respectively. In some cases a dense layer is intercalated between the connecting ring and the septum along the adnation surface, which has been called the *"adnation layer,"* causing a *"false adnation surface."*

On account of its delicate nature the connecting ring is frequently destroyed during or after the deposition of the shell into the sediment,[1] or during the process of weathering. The sometimes poor state of preservation is mainly responsible for the opinion maintained by a number of authors that the connecting ring should be perforated by foramina, serving the exchange of gas or fluids between the siphuncle and the air chambers. A careful examination of well-preserved specimens, however, always results in the observation that such foramina do not exist. It can be shown that under favorable conditions of imbedding and fossilization no trace of foramina in the connecting rings can be discovered, and the supposed existence of foramina in certain specimens is due to some formerly unknown peculiarities of the so-called obstruction rings which will be discussed on the following pages.

b. *The "Obstruction Rings."*

The deposits within the siphuncle which are long known as obstruction rings, exhibit a considerable variability in appearance. In many cases they appear as evenly shaped ring-like

---

[1] It can, therefore, be questioned whether the absence of connecting rings in specimens of the Upper Cambrian genus *Plectronoceras* really has to be regarded as a primitive feature (Ulrich and Foerste, 1933) or rather is due to the mode of preservation.

deposits around the septal neck, but the expression obstruction "rings" is hardly justified in the great number of cases, where those deposits are rather irregular in shape and sometimes, especially in the older segments of the siphuncle, arranged in an extremely complicated manner.

It has been the prevailing opinion that these obstruction rings began to develop in the "open space" of the siphuncle as the animal grew older and that more or less incidentally they did not happen to occupy finally the entire interior of the siphuncle, leaving free certain parts known as the endosiphuncular tube and the radial canals or diverticula. The latter were sometimes thought to stand in connection with the supposed openings in the connecting rings, the absence of which has just been mentioned. A closer examination of the shape of the endosiphuncular tube and particularly of the arrangement of the radial canals and related features leads to an entirely different view upon the subject.

A most important peculiarity of the obstruction ring deposits is that they never touch the inner side of the connecting rings in any considerable extent, except on those parts of the connecting rings which are adnate to the septum. The free part of the connecting ring remains free from contact with deposits situated within the siphuncle. The open space left between the obstruction rings and the connecting ring has been called *perispatium* and is regarded as a very important feature in connection with the explanation of the endosiphuncular structures of the actinoceroids.

A comparative study of different genera of actinoceroids reveals that the perispatium is represented in every specimen where, according to the prevailing conditions of preservation, it can be reasonably expected to be preserved. Naturally, where the connecting ring is removed by invading matrix, the perispatium cannot be preserved.

It can clearly be shown that the possibilities of growth of the endosiphuncular deposits (obstruction rings) are limited to a certain space beyond which no further enlargement is possible. This is the entire space not occupied by the endosiphuncular vascular system and the perispatia. This fact, of course, can best be seen in the lower part of the siphuncle where the obstruction rings have reached their maximal stage of growth. The upper part of the siphuncle, where the obstruction rings are still in the early stage of their development, furnishes no complete information pertaining to the structural details of the interior of the siphuncle. In the upper part of the siphuncle a more or less wide open space, later on filled with matrix, is left open by the not fully developed obstruction rings. While the obstruction deposits are enlarging from one segment to the other, this central space becomes narrower and in many cases its outer appearance is that of the endocone of the endoceroids. However, since the shape of this cone has no bearing upon the explanation of the anatomy of the siphuncle, I introduced the name *pseudoendocone* for it. The obstruction rings are of a "centrifugal type," when they first tend to fill out the marginal part of the siphuncle, they are "centripetal" when developing around the septal neck, thus first constricting the septal foramen. Only really ring-like deposits of this kind deserve the name "obstruction rings."

Another type of endosiphuncular deposits develops without any connection to the obstruction rings just discussed. These are deposits frequently to be found within the perispatium and they may conveniently be called *perispatial deposits*. Usually they develop during later stages after the obstruction deposits are more or less completed, though sometimes they can be found to grow at earlier stages of growth, when the deposition of obstruction-ring material is not yet entirely completed and the obstruction rings have not yet reached their maximal stage of growth. Perispatial deposits are always found in distinct layers indicating a progressive growth, when the open space of the perispatium, at least in its entire original extent, was not needed any longer.

c. *The Endosiphuncular Vascular System.*

When an investigation of the arrangement of the endosiphuncular deposits or rather of the arrangement and structure of the "open spaces" between these deposits is made, a system of canals and tubes reveals itself which is arranged in such a systematic manner that it is difficult to explain otherwise than by regarding it as something that originally must have been a system of vascular tubes.

These investigations started from a collection of actinoceroids, mainly consisting of species of *Elrodoceras*, from the Silurian Racine dolomite. These fossils were dolomitized in such a way that all parts, which were solid at the life-time of the animal, had been dissolved, at the present state of preservation, presenting open spaces, whereas all those parts, which were formerly open and became filled with matrix after the deposition of the shell into the sediment, were dolomitized and are now solid. Thus, within the siphuncle of these specimens we obtain a natural cast of the entire space, which has not been occupied by endosiphuncular or obstruction deposits. Though the process of dolomitization, of course, has destroyed many of the more delicate structures, those specimens give an excellent idea of the arrangement of the canals and tubes in the interior of the siphuncle. Studying these structures it at once becomes evident, that they are arranged in a conspicuously systematic manner.

In general it was possible to distinguish between several kinds of structural arrangement of the endosiphuncular tubes.

The simplest type is represented by *Actinoceras ruedemanni* Foerste and Teichert and related forms. At the passage of the endosiphuncular tube through the septal foramen or a little above, about 20 radial tubes diverge from the central tube and approach the perispatium evenly curved. To this type belong most species of *Actinoceras*, a larger group of *Armenoceras*, the members of the family *Huroniidae* and the genera *Kochoceras* and *Lambeoceras*.

Of a more complicated character is the endosiphuncular structure of *Nybyoceras* and others. In specimens of the *Nybyoceras* type the radial tubes present themselves in a system of arcs, sometimes arranged in a rather intricate manner. In some genera these arcs branch into several tubes when approaching the perispatium. Of the *Nybyoceras* type are the siphuncles of *Nybyoceras*, *Cyrtonybyoceras*, *Selkirkoceras*, of some species of *Armenoceras* and most probably of *Gonioceras*, though the latter is often simpler in structure.

The endosiphuncular structure of *Elrodoceras* has been regarded as a third type, which occupies an intermediate position between the two formerly mentioned. The radial tubes in *Elrodoceras* are distinctly arc-like, but they are in closer contact with the central tube than in *Nybyoceras* and similar forms.

Another type is represented by *Deiroceras* and a group of *Ormoceras*, showing a rather wide endosiphuncular canal and simple, straight, thin radial tubes which branch off from the central tube about in the middle plain of the segments.

In a number of genera as *Cyrtactinoceras*, *Paractinoceras*, *Megadiscosorus*, *Discoactinoceras* and others the structure of the siphuncle is too insufficiently known to permit any definite conclusions.

It is quite evident that these endosiphuncular structures cannot be regarded as mere openings within the siphuncle, left free in a more or less incidental way by the growing obstruction deposits. These systems of canals or tubes are so complicated, that it must be assumed that they existed already long before the obstruction deposits were formed and that their origin is quite independent from the formation of the latter. Therefore, we arrive at the conclusion that the system of tubes within the siphuncle was once a *system of organic vascular tubes* during the life of the animal. The hypothesis is put forward, that this vascular system has been embedded in some kind of *organic tissue*, by calcification of which the so-called "obstruction rings" were formed and the organic tubes could be preserved in their original arrangement (Fig. 3).

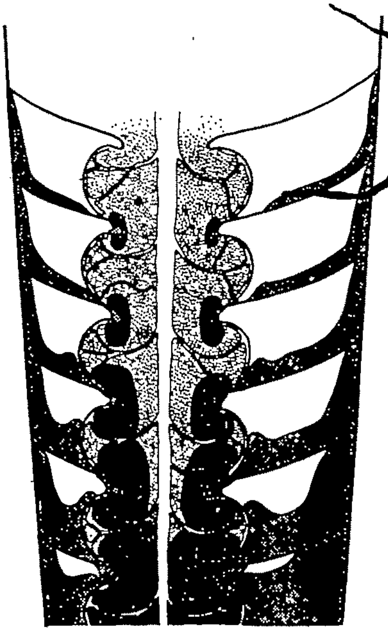


Fig. 3. Diagrammatic sketch, showing the development of "obstruction rings" by calcification of the endosiphuncular organic tissue. (White: endosiphuncular vascular system and free space within the air chambers. Stippled: endosiphuncular tissue. Black: calcified parts of the endosiphuncular tissue. Crossed: intracameral deposits.)

Both the vascular system and the organic tissue surrounding the latter must have had important organic functions, the nature of which we can only guess. It was necessary to transport solid material in a dissolved state through the porous walls of the segments into the air chambers in order to build intracameral deposits above and below the septa. Since the connecting rings do not possess foramina which could serve this purpose, the open space of the perispatium must have been of some importance for the transportation of fluids. In this way these could be evenly distributed all around the siphuncular segment and could continuously be pressed through the segmental wall.

According to the progressive growth of the animal the endosiphuncular tissue of the earlier segments became superfluous and gradually was calcified.

In the upper part of the siphuncle the calcification of the endosiphuncular tissue was not yet completed—the "obstruction rings" have not yet reached their maximal stage of growth. The tapering cone-like space in the upper part of the siphuncle, the pseudoendocone, which can be met within a number of actinoceroids, results from the incompleteness of the calcification of the endosiphuncular tissue in this part of the siphuncle. Here the vascular system cannot be found preserved in fossil state.

It is of importance that in some cases it has been observed that the structure of the "obstruction rings" is that of concentric lamellae (Teichert, 1934). This is a conspicuous analogy to the development of endosiphuncular sheaths in endoceroids. However, whereas the sheaths in endoceroids run parallel to the endocone and the latter originates by the cone-shaped form of the sheaths, the pseudoendocone of the actinoceroids results from an increase in number of lamellae in an apical direction, the form of the lamellae being approximately cylindrical.

The Intracameral Deposits (*organic deposits, stereoplasma*).

Only gradually first the presence, then the importance, of solid deposits within the air chambers has been realized. We know now that these deposits can be found within the shell of various groups of shell-bearing cephalopods, in Nautiloidea as well as in Ammonoidea, though seldom observed in the latter. In connection with the organic deposit of the septa the question of the nature of the "pseudoseptum" must be considered, the latter being an intermediate lining between two real septa, which frequently has been regarded as being of a similar nature as the true septa.

The question of the intracameral deposits and of the "pseudoseptum" has been given attention in earlier days by Woodward, Dewitz, Remelé, Mascke, Noetling, Blake, Holm, Meek and Worthen, Mojsisowicz and particularly by Barrande, later on by Hyatt and Pompeckj and more recently by Grabau, Croneis, Endo, Kobayashi and the present writer. Foerste and Teichert in 1930 doubted the validity of the "pseudoseptum" and the intracameral deposits in the use of classification. The latter view probably is still right. Kobayashi, when regarding the presence of intracameral deposits as an important feature of the actinoceroids, is quite right as far as the actinoceroids of Eastern Asia are concerned. This feature, however, loses much of its importance, when we turn to the actinoceroids of North America and Europe and no satisfactory explanation exists for the almost constant presence and regularity of the intercameral deposits among the Asiatic actinoceroids. Moreover, considerably large groups of decidedly non-actinoceroid cephalopods exhibit beautifully developed intracameral deposits as has been particularly well shown by the investigations of Barrande.

Considering the most important features of the intercameral deposits we can easily distinguish between three different kinds of them. The first one is deposited on the upper side of the septa and the term *episeptal deposits* has been proposed for them. Another kind is deposited on the lower surface of the septa and has been called *hyposeptal deposits.* Hyposeptal in its nature, but mostly independently developed, is a deposit along the outside of the septal necks, filling the concavity caused by the outward curvature of the septum. This layer is comparatively rare. When present, it usually does not stand in connection with the hyposeptal deposits. It has been given the name *supporting ring* ("Stützring"), because it is thought to strengthen the constriction of the siphuncle at the septal neck.

The episeptal deposits may occur alone or in connection with either the hyposeptal deposits or the supporting ring or both, but never do hyposeptal deposits develop alone. They do not even begin to form earlier than the episeptal deposits in case of both kinds of deposits being present. If both types of deposits develop, they either begin simultaneously or the episeptal deposits start earlier.

In many cases the episeptal deposits show a particularly remarkable growth along the outer side of the connecting ring, forming a distinct "*circumsiphuncular ridge*" around the segment of the siphuncle, elevated above the surface of the episeptal deposits in the rest of the camera. It is not known what the cause of this peculiar growth of the episeptal deposits in the vicinity of the siphuncle may be. But since the material, by which the deposits are built up, must be supplied from the interior of the siphuncle through the porous wall, it may be assumed that an especially large part of the material thus transported was precipitated in the immediate neighborhood of the siphuncle.

To understand the shape of the episeptal deposits it is necessary to investigate the shape and extension of the septa. Tracing these towards the wall of the conch one will find them to continue upward along the inner side of the wall of the conch for the entire length of the camera. This forward directed part of the septum has been called its *mural part.* It is quite evident that, if episeptal deposits are developed, they are to be expected to be found, not only upon the septa dividing the different camerae, but also along the side walls of the camerae, as deposited on the mural parts of the septa.

Speaking of intracameral deposits in general, one should be well aware of the fact that deposits within the air chambers can originate also by infiltration of inorganic matter after the deposition of the shell into the sediment. Deposits of such kind may be called *secondary deposits.* Their appearance is fundamentally different from that of the primary deposits. If the connecting ring is preserved, we may expect the secondary deposits to precipitate also along the latter, or, if the connecting ring is destroyed, the secondary deposits usually follow the entire septum around the septal neck. Of course, nothing of this kind could happen while the animal was still alive. Under normal circumstances there will be no trouble in distinguishing both kinds of deposits.

Shape and development of the primary intracameral deposits can be very different. In many cases they are but slightly developed in the lower part of the conch, increasing in thickness towards the middle part and again decreasing and sometimes disappearing in the uppermost camerae. Sometimes, however, we find the entire lower part of the conch filled out with solid deposits, gradually decreasing in size towards the upper end of the specimen. This is true for some Actinoceroids, but especially for a great number of Bohemian Orthoceroids as described by Barrande. The biologic purpose of the intracameral deposits must have been to balance the buoyancy of the air chambers. It still remains to be considered, why intracameral deposits, as it appears, are not a feature common to the majority of shell-bearing cephalopods.

Fig. 4 gives an idea of the variability in appearance of the intracameral deposits.

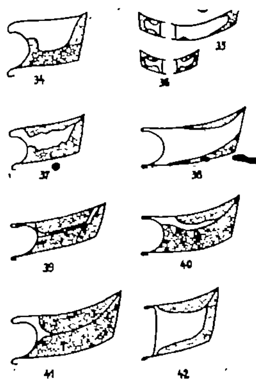


Fig. 4. Diagrammatic sketches of several types of intracameral deposits. 34. Episeptal deposits with circumsiphuncular ridge. 35. Intracameral deposits of *Westonoceras* in dorso-ventral section. 36. Intracameral deposits of *Westonoceras* in lateral section. 37. Episeptal and hyposeptal deposits with irregular surface. 38. Slightly developed episeptal and hyposeptal deposits. 39. Strongly developed episeptal and hyposeptal deposits as in some species of *Stereoplasmoceras* Grabau. 40. Strongly developed episeptal and slightly developed hyposeptal deposits as in some species of *Stereoplasmoceras* Grabau. 41. Chamber nearly completely filled with intracameral deposits and formation of a "pseudoseptum" as in *Rayonnoceras* Croneis. 42. Evenly distributed episeptal and hyposeptal deposits with beginning of a pseudoseptum.

Mode of Life.

A discussion of the mode of life of the Actinoceroids cannot be based on very safe conclusions. It is, however, reasonable to assume, that forms with very large and heavy siphuncles, forms which are known to have strongly developed intracameral deposits, and finally forms with a distinctly flattened ventral side show a decided adaptation to benthonic life. To this group we may assign the following genera:

Kochoceras and *Selkirkoceras*, large siphuncle, distinctly flattened ventral side.

Rayonnoceras, *camerae* and siphuncle almost entirely filled out by solid deposits.

Several species of *Actinoceras* and *Armenoceras* with wide siphuncles or abundant intracameral deposits.

A second group may have been capable of swimming, but perhaps mainly inclined to a benthonic life. Most species of *Actinoceras* and *Armenoceras*, *Nybyoceras*, the *Huroniidae*, *Gonioceratidae* and possibly *Saffordoceras*.

The curved Actinoceroids, all of them conspicuously lacking a distinct flatness of the ventral side, may have been mainly swimming: *Troostoceras*, *Elrodoceras*, *Megadiscosorus*, *Cyrtonybyoceras*, *Cyrtactinoceras*.

None of these develop intracameral deposits of any considerable extent, which also indicates a swimming mode of life. The same may be concluded for *Ormoceras*, *Deiroceras* and *Sactoceras*, on account of their usually small size, their rounded cross-section and their lack of intracameral deposits.

To the swimming forms certainly the *Westonoceratidae* must be added.

This tabulation shows that among the *Actinoceratidae* as well as among the *Armenoceratidae* both swimming and benthonic forms are represented. Phylogenetically the benthonic adaptation is very likely to be the primary one, whereas the swimming forms represent later branches, the development of which stands in close connection with degenerative processes of the siphuncle within certain groups of the Actinoceroids.

The benthonic forms, however, were the more or less persistent ones. The last representation of the Actinoceroids is the genus *Rayonnoceras* in the Mississippian of Oklahoma and the Lower Carboniferous of England. It is by far the largest Actinoceroid we know of and at the same time its endosiphuncular and intracameral deposits show such a hypertrophical development, that a benthonic life of that animal can be assumed with certainty.

Ontogeny.

An investigation of specimens of the genus *Kochoceras* from North Greenland brought to light a number of facts which disclose some of the main aspects of the ontogeny of the actinoceroids (Teichert, 1934). It is characteristic of actinoceroids that they do not taper to a point as the Endoceratidae and apparently many other straight forms do, but end bluntly.

The last segment of the siphuncle is of about the same size as the following segments. In some instances it is inconsiderably smaller, but in other cases it is somewhat larger than the next-following one. This first segment occupies the greater part of the initial chamber. The rate of enlargement of the diameter of the conch is comparatively little.

It follows, that the actinoceroid animal possessed a rather large size when it began to secrete a solid conch. Its body was certainly considerably larger than that of orthoceroids and particularly of nautiloids at the same stage of their development. At the same time with the formation of the first septum the creation of the first siphuncular segment took place, which was very large in comparison with that part of the body, which at that time occupied the living chamber. The further development of the growth of the animal is mainly characterized by the growth of the siphuncular substance, whereas the body occupying the living chamber enlarges in a smaller rate. This is contrary to the conditions in orthoceroids and nautiloids, where the growth of the body is more rapid and the increase in siphuncular organic substance inconsiderable.

Within the last segment almost always an increase in diameter of the endosiphuncular tube can be observed. It seems that an apical aperture of the conch exists, where the endosiphuncular tube ends, but it is still undecided whether such an aperture was held open during the life of the animal.

Development of the Actinoceroids.

Though our knowledge of the distribution and development of the Actinoceroids is far from being complete, a point is reached where it seems to be advisable to sum up the data at hand. During recent years considerable progress has been made in the study not only of the actinoceroids, but also of other groups of nautiloids in a broader sense. Still the problem as to the origin of the cephalopods remains unsolved. I shall not endeavor to enter into many speculations of that kind, but mainly restrict myself to actinoceroids proper.

Since Hyatt's time the shape and size of the septal neck (septal funnel) have played the most important rôle in the classification of the nautiloids. Quite recently newly revealed facts have led the present writer to doubt the usefulness of basing the classification on this feature instead of on others possibly more important. The same doubts have been independently expressed by Kobayashi in a recent publication. We know now, that in the same specimen the character of the septal neck may change from holochoanitic to cyrtochoanitic or orthochoanitic, from orthochoanitic to cyrtochoanitic, or from an actinoceroid to an armenoceroid type, either continually or irregularly. Serious doubts as to the systematic position of such specimens may arise, when the shape of the septal neck alone is taken as a criterion. Realizing the fact that, when the cephalopods are arranged under the present system of classification, we will find very different siphuncular structures among the different members of each group, Troedsson (1932) spoke of endoceroid, orthoceroid, and actinoceroid structures of the siphuncle, all of which could be found to develop within siphuncles of genera of each of the three larger groups of cephalopods. Recognizing, however, that the siphuncle is part of the body of the animal and its form and structure, therefore, reflects the organization of a part of the living animal, it at once becomes evident, that it is an impossibility to maintain classificatory principles by which animals with widely divaricating organization of the body are placed in the same systematic group.

It seems safer and at the same time more in accordance with biologic principles to pay more attention to the interior structure of the siphuncle as exhibited by those deposits which can be preserved. This still leaves us in a doubtful position with regard to the character of siphuncles lacking interior deposits, but nevertheless recent investigations seem to show that we are on safer ground when taking the structure and organization of the siphuncle as our basis of classification.

Therefore, the present writer proposed to abandon Holochoanoidea, Orthochoanoidea, and Cyrtochoanoidea as classificatory terms, though they may still conveniently be used in explaining the structures of the septal necks in individual groups. The length and the shape of the septal necks and in consequence the expressions holo-, ortho-, cyrtochoanitic may be used in the delineation of families and even genera or species. A similarity of the endosiphuncular structures counts heavier in favor of the kinship of various forms than a congruency of the septal necks, the bearing of which on systematics doubtlessly has been overestimated.

To replace the former terms the present writer proposed the names: *Endoceroidea* (largely identical with, but not entirely covering the former Holochoanites), mainly comprising forms with comparatively wide siphuncles containing a great variety of sheath-like deposits and horizontal diaphragms. The latter group, however, for which recently Hyatt's term "Diphragmida" has been successfully revived by Ulrich and Foerste, might eventually prove to be quite independent.

Actinoceroidea (largely identical with, but not entirely covering the annulosiphonate group of the Cyrtochoanites), comprising forms with mostly wide nummuloidal siphuncles and a distinctly developed endosiphuncular vascular system.

Cyrtoceroidea (identical with that part of the Actinosiphonate group of the Cyrtochoanites which actually shows radial lamellae within the siphuncle as true *Cyrtoceras* does). Very little is as yet known about the organization of this group.

"*Gomphoceroidea*," a group with mostly wide siphuncles of unknown interior structure. The name is provisional. The group may comprehend a variety of incoherent types of animals.

Nautiloidea sensu stricto, a term which should only be applied to the stenosiphonate, orthochoanitic forms with a siphuncle either degenerated or serving other purposes than that of the foregoing groups.

The Ammonoidea and the Nautiloidea, the latter in the sense here applied, have been linked closer together by recent investigations of Schindewolf. It may, therefore, become possible to divide the entire group of shell-bearing cephalopods in the two large sub-orders of the *Stenosiphonata* (Nautiloidea, Ammonoidea) and the *Eurysiphonata* (Endoveroidea, Actinoceroidea, Cyrtoceroidea, "Gomphoceroidea").

At present no really successful attempt could be made to link these two large groups together. Among the groups, however, belonging to the eurysiphonate branch of the cephalopoda we may be able to trace a few connections and point out some possibilities.

Several attempts have been made to derive the actinoceroids, or rather that entire extremely heterogenous group which has been called Cyrtochoanites, from the Orthochoanites or Nautiloidea s. str.

It must, however, be borne in mind, that the first known actinoceroids are forms with considerably wide siphuncles, such as *Maruyamaceras* from the Chazyan of Manchuria and *Nybyoceras* from the same formation in Manchuria and Oklahoma. On account of its age as well as on account of its structural features *Maruyamaceras* may well be regarded as an ancestral

Centripetal type of obstruction rings: developing first concentrically around the septal neck and rapidly constricting the septal foramen.

Endosiphuncular tissue: hypothetical organic tissue, by calcification of which the so-called obstruction rings are supposed to have originated.

Maximal stage of growth of the obstruction deposits: the stage of growth beyond which no further development of obstruction deposits is possible, because all of the endosiphuncular tissue is calcified.

Pseudoendocone: the space which is left free between the obstruction deposits of the centrifugal type in the upper part of the siphuncle; without significance for the explanation of the organic structures of the endosiphuncle.

Perispatium: free space between central obstruction deposits (or endosiphuncular tissue) and connecting ring.

Perispatial deposits: deposits in the upper and lower end of the perispatium, developing when the entire space of the perispatium is no longer needed.

Mural part of the septum: that part of the septum which is attached to the inner side of the shell.

Intracameral deposits: deposits of solid material within the air chambers, "*primary*" when developed during the life of the animal by organic action, "*secondary*" when built afterwards by inorganic infiltration.

Episeptal deposits: primary deposits on the upper side of the septum and along the mural part of it.

Circumsiphuncular ridge (Zirkumsiphonale Leiste): thickening of episeptal deposits in the immediate neighborhood of the connecting ring.

Hyposeptal deposits: primary deposits on the lower side of the septum.

Supporting ring (Stützring): primary deposit on the concave outer side of the septal neck.

The diagrammatic sketch on Fig. 2 shows as many of these essential features as possible.

CLASSIFICATION.

A provisional classification of the Actinoceroids was first undertaken by Hyatt in 1900, who divided them into *Loxoceratidae*, *Uranoceratidae*, and *Actinoceratidae*. After the establishment in recent years of a number of new genera as

Armenoceras, *Elrodoceras* and others by Foerste, Troedsson pointed out the peculiarity of the entire armenoceroid group, characterized by short septal necks, proposing tentatively a new family *Armenoceratidae*.

This was adopted by Foerste and Teichert in 1930, who furthermore rearranged the then known genera in a new classificatory attempt.

Results of more recent studies made necessary a few additions and changes. A closer study of specimens assigned to *Discosorus* and allied genera (Teichert, 1931) forced the present writer to remove this group from the Actinoceroids. They were regarded as a distinct family, consisting of *Discosorus* Hall, *Stokesoceras* Foerste, and *Endosicosorus* Teichert, with doubtful affinities, but certainly not belonging to the Actinoceroids.

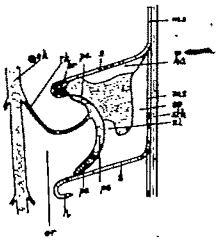


Fig. 2. Diagrammatic sketch, showing the most important features of the siphuncle and air chamber of an actinoceroid. ek, endosiphuncular tube; rk, radial canal, or obstruction ring; ps, perispatium; pa, perispatial deposits; s, septum; k, brim; ms, mural part of the septum; sch, shell; ep, episeptal deposits; zl, circumsiphuncular ridge; ha, hyposeptal deposits; sr, supporting ring.

In 1933 the present writer regarded *Westonoceras* as a type of a new family then being the only genus of it. Since then another genus closely related to *Westonoceras* and belonging to the same family has been described by Foerste as *Teichertoceras*. At the same time *Maruyamaceras*, a new genus of the *Actinoceratidae*, has been established by Kobayashi and *Cyrtonybyoceras*, a new armenoceroid, by the present writer. Furthermore, study of the type material of *Calhounoceras* Troedsson has convinced the writer that this genus was rightly placed by Troedsson among the Actinoceroids. Its more exact position, however, is uncertain. The scheme given below follows essentially the arrangement published in 1933 with the necessary additions according to our increased knowledge:

type of the actinoceroids or at least to be very near to it. From a *Maruyamaceras*-like type straight lines of development can be traced in almost every direction to the different branches of the actinoceroid groups. By preservation of the septal neck and a decrease in width of the siphuncle true actinoceratid forms may develop which can be traced upward until the Carboniferous to its last representative *Rayonnoceras*.

A side branch of this group may be the family of *Sactoceratidae* with greatly decreased siphuncle. From this point of view the *Sactoceratidae* represent a remarkably degenerated group of the actinoceroids.

Another large group which may have arisen from the ancestral *Maruyamaceras*-like type is represented by the *Armenoceratidae,* which resulted from an advancing shortage of the septal neck. Whether *Armenoceras* or *Nybyoceras* is the older type is difficult to decide. *Nybyoceras* makes its first occurrence in older beds than *Armenoceras,* but yet the *Armenoceras*-type has a more primitive significance. The decidedly excentric siphuncle as in *Nybyoceras* is usually regarded as a feature of more advanced specialization.

Apparently a direct offspring from *Armenoceras* or *Nybyoceras* is a group of curved animals, beginning with *Cyrtonybyoceras* and developing into *Megadiscosorus* and *Elrodoceras* in Silurian time. A descendant of *Nybyoceras* is *Selkirkoceras* with its flattened ventral side and with a siphuncle attached to the latter, a parallel to the *Kochoceras* branch of the *Actinoceratidae.*

A separate branch of the *Armenoceratidae* is represented by the *Huroniidae* and also by the *Gonioceratidae.* Both families have many features in common with the *Armenoceratidae,* but are both specialized in different directions.

Regarding the general tendencies of development the trend is rather to diminish the diameter of the siphuncle than to enlarge it, as it is usually assumed. It is the earliest forms of the actinoceroids that are characterized by large siphuncles. Among the younger representatives, in the Upper Ordovician as well as in the Silurian, the number of species with smaller siphuncles increases considerably, in fact, in the Silurian, actinoceroids with very wide siphuncles are rather uncommon.

With these facts in mind the suggestion lies quite near to derive the actinoceroids from other eurysiphonate forms rather than from stenosiphonate ones. It seems that in actinoceroids a wide siphuncle, not a narrow one, is a primitive feature.

Therefore, in my opinion, all attempts that have been made to connect genetically the Actinoceroids with the Orthochoanoidea (or Nautiloidea s. str., as I would prefer to call them) are likely to fail. It is true that Nautiloidea may be able to develop features of the siphuncle which in a certain degree can resemble those known in Actinoceroids. A slight inflation of the segments can be observed, rings of solid material around the septal necks may be built. But these features may very well be regarded as occasional convergencies, as they are frequently a hindrance for the delineation of true phylogenetical connections. In the same way intracameral deposits are common among the Nautiloidea which certainly does not impose the necessity of phylogenetic relationships to the actinoceroids, where they are more common.

It does not seem unlikely to suppose that the Actinoceroids branched off from some group of the Endoceroidea. As we now know, not all Endoceroidea are holochoanitic. In some very peculiar forms especially of Asiatic Endoceroidea the septal funnel does not reach the next septum. Between the end of the funnel and the next septum an outwardly curved connecting ring is intercalated, reminding strongly of actinoceroid structures of segmental walls. In these cases the outer appearance of the siphuncle is rather that of an actinoceroid, whereas the endosiphuncular structures, though not very well preserved, still seem to be that of an endoceroid. Forms of this kind have been described by Kobayashi as *Multicameroceras* and *Sinoeremoceras* from the Canadian of Manchuria.

Like the actinoceroids, these endoceroids are characterized by the presence of an endosiphuncular tube. In both cases the siphuncle is wide and must be regarded as having contained some important parts of the body of the animal. The endosiphuncular tube, the most important part of the siphuncle organ, was imbedded in the endosiphuncular tissue, which in most cases became calcified. The radial canals, radiating from the endosiphuncular tube and so characteristic for the Actinoceroids must represent a later stage of development, following the inflation of the siphuncular segments which already took place during the endoceroid stage of development.

A difficulty still represents itself in the fact that *Multicameroceras* and *Sinoeremoceras*, the two genera mentioned above, show marginal siphuncles. It is the general assumption that in all lines of cephalopod development the marginal position of the siphuncle indicates a later and more specialized stage. If this is true, *Multicameroceras* and *Sinoeremoceras* could not be supposed to be the immediate forerunners of the actinoceroids, but we would have to look for related types with the siphuncle situated in some distance from the wall of the conch.

In my opinion the cephalopods with narrow siphuncles as best known in *Orthoceras*, *Nautilus* and others, in other words the group to which I should like to restrict the name Nautiloidea, represent an entirely independent line of development. The unity and the monophyletic descent of the so-called shell-bearing cephalopoda may be seriously doubted.

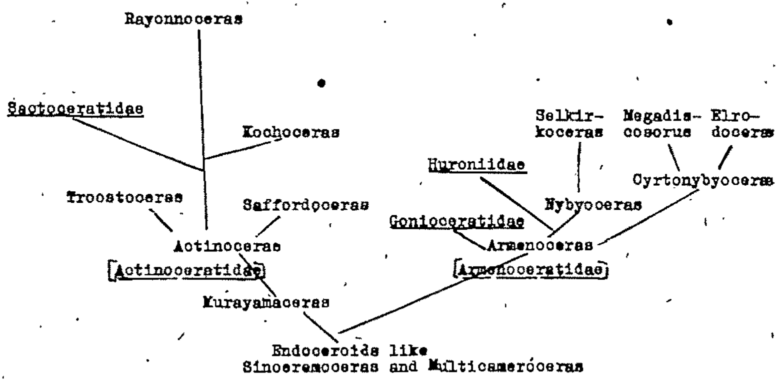
The so far known Cambrian cephalopods furnish too little evidence to settle the question. Schindewolf regarded *Volborthella* as orthochoanitic. An examination of the same material led Dr. Kobayashi and the present writer to the suspicion that this genus is more likely to show holochoanitic features. Moreover, we think that the septa are extremely close together. The writer counted about 20 of them to a millimeter.

This figure would fit with observations made on specimens of *Salterella* as given by T. H. Clark and Chr. Poulsen. However, the study of slides made from a number of *Salterella* specimens in the U. S. National Museum left the writer in a very doubtful position. These slides revealed structures essentially similar to those described by Clark and Poulsen. On the other hand it was impossible to the writer to find really conclusive evidence as to the cephalopod nature of this genus. It is doubtlessly not congeneric with *Volborthella*, which unquestionably is a cephalopod. In the specimens of *Salterella*, however, which I had the opportunity to investigate, no wall of the conch could be discovered. The nature of the "septal necks" was doubtful and even the very existence of a siphuncle was open to question. It appears that L. F. Spath (1933) is referring to similar observations, when speaking of transverse striation "more like that of certain rugose corals than of molluscan shells." However, to clear up the true nature of Salterella, further investigation is still needed.

In the accompanying table a scheme for the development of actinoceroids is proposed, which seems to be in accordance with the facts known at present. The basic principle is, that the actinoceroids are derived from eurysiphonate ancestors which may be similar to or identical with some known representatives of endoceroids. In these deductions the character of the septal neck is left out of consideration.

It was not the purpose of these lines to enter into a discussion of the phyletic relationships of other groups of cephalopods, but it may be added that even an apparently holochoanitic structure in Volborthella would not necessarily exclude the latter from the possibility of being ancestral to the so-called Orthochoanoidea.

Evolution of the Actinoceroids.



LITERATURE REFERRED TO.

Clark, T. H.: On the Nature of Salterella. Trans. R. S. Canada, 3 ser. 19, 1925.

Foerste, A. F.: Black River and Other Cephalopods from Minnesota, Wisconsin, Michigan, and Ontario. Denison Univ. Bull., Jour. Sci. Labor. 27, 1932 and 28, 1933.

——— and Teichert, C.: The Actinoceroids of East Central North America. Ibidem 25, 1930.

Hyatt, A.: Cephalopoda. In Zittel-Eastman, Text-book of Paleontology. I. 1900.

Kobayashi, T.: Studies on the Ordovician Stratigraphy and Paleontology of North Korea with Notes on the Ordovician Fossils of Shantung and Liautung. Bull. Geol. Surv. of Chosen. 9. Keijo, 1931.

———: Faunal Study of the Wanwanian (Basal Ordovician) Series with Special Notes on the Ribeiridae and the Ellesmereoceroids. Jour. Fac. Sci. Imp. Univ. Tokyo, Sect. II, Vol. III, Pt. 7, 1933.

Poulsen, Chr.: The Lower Cambrian Faunas of East Greenland. Meddelelser om Grønland, 87, 1932.

Schindewolf, O. H.: Über Volborthella tenuis Schm. und die Stammesgeschichte der ältesten Cephalopoden. Paläont. Zeitschr. 10, 1928.

Spath, L. F.: The Evolution of the Cephalopods. Biological Reviews, 8, 1933.

Teichert, C.: On the Systematic Position of the Genus Discosorus Hall and Related Genera. Amer. Mus. Novitates, 512, 1931.

————: Der Bau der Actinoceroiden Cephalopoden. Palaeontographica. 78, B, 1933.

————: Siphostrukturen und Gehäusebau von Actinoceroiden Cephalopoden aus Nordgrönland. Medd. om Grønland, 1934.

Troedsson, G. T.: On the Middle and Upper Ordovician Faunas of Northern Greenland. I. Cephalopods. Medd. om Grønland, 71, 1926.

————: Studies on Baltic Fossil Cephalopods. II. Vertically Striated or Fluted Orthoceracones in the Orthoceras Limestone. Lunds Univ. Arsskrift. N. F. Avd. 2, 6, 1932.

Ulrich, E. O., and Foerste, A. F.: The Earliest Known Cephalopods. Science, 78, 1933.

COPENHAGEN, DENMARK.

TERTIARY GRASSES AND OTHER PRAIRIE VEGETATION FROM HIGH PLAINS OF NORTH AMERICA.[1]

MAXIM K. ELIAS.

ABSTRACT.

The results of field research of 1933 indicate that the remains of grasses and other herbs, some of which were described by the writer in 1932, are of utmost importance as index fossils in the late Tertiary deposits of Nebraska and the surrounding territory. The remains of fossil herbs in the form of husks of grasses and nutlets of Boraginaceae have been collected in great numbers in more than a score of localities, and the succession of floral zones proves to be invariably the same. The writer has succeeded in tying of the majority of his floras with the horizons in which some of the best known vertebrate remains have been collected. According to the modern interpretation of the age of these vertebrate faunas, the floral zones of the writer range from middle Miocene to middle (and probably even to upper) Pliocene. A new genus of fossil grasses, *Stipidium*, is described, and the general trend of evolution of Stipideae is outlined.

INTRODUCTION.

The existence of fossil remains of prairie grasses was first recognized in 1931 (2, p. 150). The fossils come from the late Tertiary deposits of the High Plains region, and as yet they have not been collected outside of this area. Field research in 1933, which was conducted largely on a grant from the Marsh Fund of the National Academy of Sciences, proved that the remains of grasses (and other herbs), mostly in the form of hollow husks, furnished by far the most important fossil material for stratigraphic studies of the late Tertiary continental formations.

OCCURRENCE.

The fossil grass husks are comparatively very common and are beautifully preserved, being apparently buried not far from their place of growth. The remains can be found at almost any outcrop, provided it is large enough to show several successive beds, as the remains are not found in all beds of the geologic sections but are scattered along certain horizons; rarely they are concentrated in small spots, measured by inches in diameter, or fill up small pockets in the rock.

The succeeding horizons, which contain the same leading types of herbs, constitute natural stratigraphic zones. The thickness of these zones is measured in scores of feet. The succession of these floral zones proves to be the same everywhere within the studied areas in western Nebraska, northwestern Kansas and adjacent part of Colorado. The same assemblages of plant remains were also found on reconnaissance trips to south-central South Dakota and north-central Texas.

---

[1] Published by permission of the State Geologist, Kansas Geological Survey.

PREVIOUSLY KNOWN FOSSIL GRASSES.

Fossil grasses have previously been not entirely unknown to science (4, 5, 8, 9), grass-like remains being occasionally collected among the foliage and fruits of the late Cretaceous and Tertiary arboreal plants (which comprise the bulk of paleobotanical collections). These remains, however, consist of fragmentary linear leaves and herbaceous stems and culms, rarely accompanied by imprints of crushed paniculate fertile shoots. The classification of these imperfect remains with this or that living genus of grasses is in most cases quite arbitrary. The references by the famous Baron Heer of some of the best grass remains of this kind from the European late Tertiary to the living *Oryza* and *Panicum* were severely and justly criticized by other high authorities on living and fossil plants, and at best are considered not proved. Only the presence of *Arundo, Phragmites,* and perhaps of *Bambusa* in the late Cretaceous and Tertiary beds was considered as being established on sufficient fossil evidence. The living representatives of these grasses are tall water-loving species which dwell along the shores of ponds and streams. The association of their fossil relatives with the arboreous vegetation permits no doubt that in the late Cretaceous and Tertiary times they grew in the same environment.

PRESERVATION AND ASSOCIATION OF FOSSIL PRAIRIE GRASSES.

The beautifully preserved husks of grasses in the late Tertiary formations of the High Plains are remains of an entirely different kind and origin. They are not imprints, but are siliceous petrifactions, the silica of which, at least in part, is the original mineral skeleton of the plant. They are embedded not in clays or other fine sedimentary material, where most known fossil plant imprints are found, but are restricted almost exclusively to sands and unsorted grits, the separate pebbles in the latter being up to 1 cm. in diameter. The only nonherbaceous plant, the remains of which is found in association with the grasses, is hackberry (*Celtis*), a typical xerophitic tree, sometimes dwarfed to a shrub, which is now infrequently found in ravines and valleys of the High Plains. Other plant remains of the fossil association belong to several herbaceous genera of the Borage family and to *Yucca* (provisional reference of two forms of fossil trunks), which are also distinct xerophites. The whole assemblage undoubtedly represents the remains of the late Tertiary prairie vegetation, with which we only now begin to make a real acquaintance.

TYPES OF FOSSIL GRASS HUSKS.

The husks of two species of fossil grasses, as they are now recognized, were collected in Kansas as early as 1884 by John B. Hatcher, and described in the important pioneer work by E. W. Berry in 1928 (1, p. 2) as *Lithospermum fossilium glabrum* and *Lithospermum fossilium aristatum*. Their true nature as remains of grasses was established by the writer in 1932 (3, pp. 346-349), when he also described two new species of grasses collected by himself and referred to *Panicum* and *Stipa* (3, pp. 342-345). For the *glabrum* species, which was identified and re-described by him on his own material, a new generic name, *Berriochloa,* was introduced, while the species *aristatum* was questionably referred to the same genus. Now, after examining the cotypes of *aristatum,* which are deposited in the U. S. National Museum, the writer proposes to classify this species together with many new ones which he has collected under the new generic name *Stipidium,* a fossil grass closely related to the living *Stipa* or spear-grass.

MORPHOLOGY OF GRASS HUSKS.

Since the subject of fossilized husks of grasses is entirely new, a brief introduction to the morphology of the fertile parts of living prairie grasses, with which they are to be compared, is necessary. The grain of cereals and other living grasses is usually enclosed in a husk or protective cover and the two are dispersed together, forming what is commonly known as grass seed. The protective cover is usually made of two glumes or bracts, the fertile glume or lemma and the pale or palea. The two adhere closely to the grain, the palea from the inner side or the side facing the rachis, and the lemma from the outer side. The lemma is almost always larger than the palea. The lateral edges of the lemma usually overlap to greater or lesser extent the edges of the palea, and in some genera the palea is entirely enveloped by the lemma, as for instance in *Stipa*, the lemma of which is convolute. The palea is a part peculiar to all living grasses and is not duplicated in any other monocotyledons or other plants. The essential construction of the palea in grasses varies but little. It is almost invariably two-nerved, and when it appears as a one-nerved glume, the single nerve is believed to be made by fusion of the original two nerves.

The fossil husks of grasses under discussion consist of lemma and palea, the latter being distinctly two-nerved and showing otherwise all typical features pertaining to the palea of living grasses. It is the presence of typical palea overlapped by lemma which leads the writer confidently to recognize these fossil forms as husks of extinct grasses. Both lemma and palea are more or less distinctly striated longitudinally. They are smooth or tuberculate and may be covered by hairs. At the apices of the lemmas the tubercles are modified infrequently into sharp upright bristles. At the base of some husks a hairy callus is developed. All hairs and bristles, regardless of their location on the husk, point toward its apex.

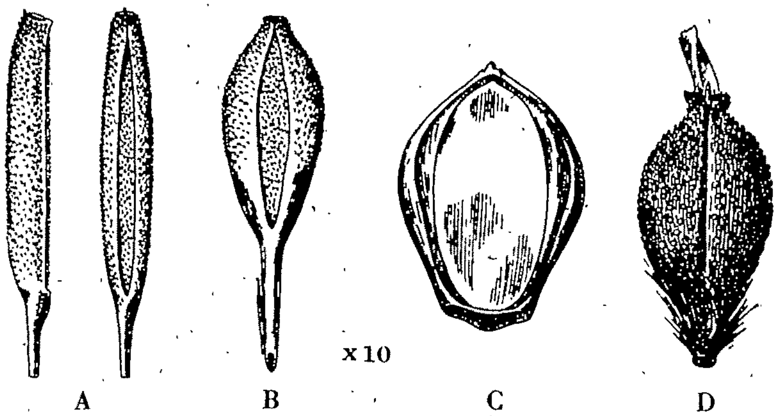
ORIENTATION OF FOSSIL GRASS HUSKS.

The two species of husks, which were originally described by Berry and re-described by the writer, do not bear any bristles or hairs, but on some of the species recently collected by the writer and referred by him to the same genera (*Berriochloa* and *Stipidium*), hairs and bristles were observed. The orientation of these hairs and bristles permits determination of which end is the apex and which is the base of these forms, and as *glabrum* and *aristatum* have a construction very similar to the newly discovered hairy species, they must be oriented in the same way as the latter. By this reasoning the writer came to the conclusion that the orientation of *glabrum* and *aristatum*, as originally set by Berry, must be changed to exactly the opposite; thus, what was considered by Berry as awn in these forms is actually sharp callus, and what was recognized as hylum (or scar of attachment, author's term) is actually the apex of these husks.

As soon as the orientation of these fossil forms is changed, their relation to living genera of grasses can be satisfactorily established. When preserving the original orientation as set by Berry, it was difficult to classify *Berriochloa* with any of the established groups of living grasses and the writer provisionally placed this fossil genus among the Hordeae. With the change of orientation it became quite clear that the fossil genus *Berriochloa* (as well as the related genus *Stipidium*) does not belong to the Hordeae, but to the group of the living *Stipa, Pitptochaetium, Oryzopsis* and others which constitute the subtribe Stipeae of the tribe Agrostideae.

THREE PRINCIPAL GENERA OF FOSSIL PRAIRIE GRASSES.

On the accompanying sketch the three principal genera of the so far discovered late Tertiary prairie grasses of the High Plains are illustrated. Figure A represents lateral and front views of the genotype of *Stipidium* n. gen. This is the smallest known species of the genus and comes from the type exposures of the lower Sheep Creek formation of western Nebraska, the well known vertebrate fauna of which is referred to middle Miocene. Figure B shows a front view of a typical species of *Berriochloa* from the same formation



EXPLANATION OF PLATE

Seeds of representatives of three principal genera of fossil prairie grasses: A—*Stipidium* n. g., n. sp.; B—*Berriochloa* n. sp.; C—*Panicum elegans* Elias; and, for comparison, D—*Living Piptochaetium* sp. All figures are magnified 10 times.

and locality. This early species of *Berriochloa* shows a very long slender callus, with few hairs still attached to it. A partly broken and apparently also fairly long callus is also well developed on the genotype of *Stipidium* (fig. A). This shows that the presence of a prominent hairy callus is an ancient feature of Agrostideae seeds, unlike the remarkable diversified awns of living *Stipa* and *Agrostis*, the development of which appendages seems to have occurred some time after middle Pliocene time (the observed related forms of this and earlier ages do not seem to bear any hard awns).

Figure C shows a front view of *Panicum elegans* Elias from the middle Pliocene beds of the Ogallala formation of Wallace County, Kansas, which was described in 1932 (3, p. 342).[2] The front views of the husks of all these figures show the palea (in the middle) overlapped by the edges of the lemma.

Figure D gives a front view of a seed of the living *Piptochaetium* sp. from Argentina (from the herbarium specimen 1,388,635, U. S. National Herbarium). The awn in this and other known species of *Piptochaetium* is flexuose and easily breaks away. Only the basal part of it is shown on the sketch. The large sharp bristle at the apex and between the edges of the lemma is protruding cuspidate apex of concealed palea. All sketches were prepared by the writer.

STRATIGRAPHIC DISTRIBUTION OF THE PRAIRIE PLANTS.

The fossil prairie flora of the High Plains, as collected and identified up to date,[3] consists of about 18 species belonging to two tribes (Paniceae and Agrostideae) of grasses (only four of which were previously described), five species of Boraginaceae herbs (four of which were described), one species (described) of hackberry (*Celtis*), two species of trunks which are provisionally classified as *Yucca*, and a few seeds which have not been identified as yet. The Boraginaceae herbs are very common in the Pliocene, but have not been collected as yet in the Miocene. They furnish the most important and widely distributed index fossils for zoning of the lower and middle Pliocene. The succession of *Krynitzkia coroniformis* zone by *Biorbia fossilia* (ex *rugosa*) zone above was found to be faithfully repeated in a great many localities along the North Platte River and other areas in Nebraska, in northwestern Kansas, and in eastern Colorado. Grasses can be used for zoning of the beds below the *Krynitzkia coroniformis* zone, as indicated by the few collections made in undoubted Miocene strata.

---

[2] The age of these Wallace County beds was assigned to the lower Pliocene on the ground of interpretation of their rich vertebrate fauna (2, pp. 153 and 160-161). Now, however, R. A. Stirton, who is studying the entire problem of the age of North American late Tertiary faunas, refers the same Wallace County fauna to the middle Pliocene (oral communication by Dr. R. A. Stirton), which view is here accepted.

[3] Detailed description of the new species is in preparation.

GENERAL TREND OF EVOLUTION OF THE STUDIED GRASSES.

Perhaps the most important scientific result of the studies of the fossil vegetation of the prairies is the first glimpse that it provides on the evolution of some grasses through Miocene and Pliocene ages. All collected grasses belong to the tribe Paniceae and to the subtribe Stipeae of the Agrostideae (there are 14 tribes of living grasses). Only Stipeae have been found in the Miocene and lower Pliocene (in the sense now accepted by R. A. Stirton), while Paniceae have been found so far only in the middle Pliocene and in apparently higher beds (earliest late Pliocene?) from which no vertebrates have been collected. The Stipeae, which range through the whole studied section, show a very distinct evolutionary development, as their husks indicate. These husks show a general change from an open lemma of the Miocene to closed lemma of lower and middle Pliocene, and finally to convolute lemmas as in the living *Stipa* and *Aristida*, a few convolute types appearing, however, in the middle Pliocene. The earliest known (middle Miocene) husks of this tribe of grasses, which are classified as *Berriochloa* and *Stipidium*, are very small and can barely be seen with the naked eye among the sand grains of the containing rock. Although some slightly larger forms were also collected in the Miocene, these and still larger species become very common only in the lower Pliocene, where the smallest species of *Stipidium* disappear.[4] The largest known representatives of this tribe of grasses are *Berriochloa glabra* and *Stipidium aristatum*, which appear still later, in the middle Pliocene. None of the living nearest relatives of these forms seem to be as large as these middle Pliocene species. The evolutionary increase in size of the fossil Agrostideae, as revealed by the material from the High Plains, is probably more than coincidental with the well known general increase in size, through the geologic ages, of horses, camels and other herbivores which fed on these prairie grasses.

---

[4] The smallest species of Miocene *Berriochloa*, however, do not become extinct, but through evolutionary changes are connected to the living species of *Piptochaetium*, the husks of which are of about the same size (compare figs. B and D).

AGE OF THE STUDIED FLORAS.

The age of the discovered floral zones was established exclusively with the help of the few best known vertebrate faunas from the High Plains, which were studied by Osborn, Matthew, and their associates and successors. The quarries from which these faunas have been collected were carefully re-located and the plant remains were collected directly from the vertebrate-containing beds and, whenever possible, from the beds above and below them in the local geologic sections.

The following well known faunas are now securely tied with the floral zones:

(1) The middle Miocene fauna from the section of lower Sheep Creek formation 18 miles south of Agate Springs. Here the plant remains have been collected from the very same outcrop which gave Osborn his types of *Merychippus isonesus secundus*, *M. isonesus tertius*, *M. isonesus quartus*, and *M. isonesus quintus*.

(2) The fauna from the famous Sternberg quarry of Long Island, Phillips County, Kansas, formerly referred to lower Pliocene; now considered by R. A. Stirton to be middle Pliocene.

(3) The fauna from Beecher Island, south of Wray, Yuma County, Colorado. This is the rich fauna described by H. J. Cook. Formerly referred to lower Pliocene; now considered by R. A. Stirton to be middle Pliocene.

(4) Two faunas from the vicinity of Valentine, Cherry County, northern Nebraska. The collections of plants were made at the time when R. A. Stirton was opening old and new quarries in order to prove that two distinctly different zones of vertebrates are developed here; one of early Pliocene age, the other of late Miocene age. With the coöperation of Stirton and his crew, a goodly number of plant remains was collected from both zones, which were also found to occupy distinctly different stratigraphic positions in the local geologic section.

STUDIED PLANTS AS "INDEX FOSSILS."

After being tied in the most precise way to the important and recently carefully revised faunal zones of the High Plains, the floral zones can now be used for determination of the age of rocks in those numerous outcrops from which no vertebrate remains have been collected or in which they have not been found in sufficient number or were not well preserved. In coöperation with the Nebraska Geological Survey, the floral zones of the Ogallala formation were successfully carried through the outcrops of this formation along the North Platte River from Paxton to the vicinity of Scotts Bluff, and with the help of these zones some important structural features along this valley were discovered.

The Ogallala formation of Darton is a very useful geologic unit, but its uniform lithology prevented the possibility of its being zoned until the plant remains provided the necessary zone markers. Now, with the help of these zones, the total thickness of this formation can be determined more accurately. It proves to be 475 feet, whereas formerly it was believed to be only 200 to 250 feet thick, since in no single locality is the total thickness of the formation exposed.

TABLE OF FLORAL ZONES.

Floral zones as determined by the most typical plants		Geologic age as indicated by the vertebrates
Zones	Subzones	
Zone of *Celtis* cf. *willistoni* (Cockerell) 175′	Upper subzone of *Echinochloa* n. sp.	Probably late Pliocene (Vertebrate fauna unknown)
	Lower subzone	
Zone of *Biorbia fossilia* (ex *rugosa* (Berry) about 100′	Upper subzone of *Panicum elegans* Elias	Probably late medial Pliocene
	Lower subzone of *Krynitzkia chaneyi* Elias	Medial Pliocene
Zone of *Krynitzkia coroniformis* Elias about 100′		Early medial Pliocene Late early Pliocene
Zone of *Stipidium* n. sp. 100′		Earliest early Pliocene Latest late Miocene
?		Late Miocene
Zone of a very small *Stipidium* n. sp. 70′		Medial Miocene

SELECTED BIBLIOGRAPHY ON FOSSIL AND LIVING GRASSES

1. Berry, E. W.: Fossil nutlets of the genus *Lithospermum*: Proc. U. S. Nat. Mus., vol. **73**, art. 13, pp. 1-3, 1928.
2. Elias, M. K.: Geology of Wallace County, Kansas: Bull. Univ. Kansas, State Geol. Survey, Bull. 18. See pp. 149-152, 1931.
3. Elias, M. K.: Grasses and other plants from the Tertiary rocks of Kansas and Colorado: Contributions to the Paleontology of Kansas, No. 1, Sci. Bull., Univ. of Kansas, vol. **33**, pp. 333-368, 1932.
4. Gardner, J. S.: Fossil grasses: Proc. Geol. Assoc., vol. **9**, 1885-1886, p. 441, 1886.
5. Hackel, E.: Gramineae, in Engler and Prantl, Die Naturlichen Pflanzenfamilien, II Teil, 2 Abt., 1887.
6. Hitchcock, A. S.: Text-book of grasses, Macmillan Co., New York, 1914.
7. Hitchcock, A. S.: Genera of grasses of the United States: U. S. Dept. Agric., Bull. 772, 1920.
8. Hollick, Arthur: New fossil grass from Staten Island: Bull. Torrey Bot. Club, vol. **24**, pp. 122-124, 1897.
9. Lesquereux, Leo: Contribution to the fossil flora of the Western Territories: Rept. U. S. Geol. Survey Terr., vol. **7**, See pp. 85-91, 1887.

WASHINGTON, D. C.

THE YALE FOSSILS OF ANTHROPOID APES.

ALEŠ HRDLIČKA.

In the March ('34) number of this Journal Mr. G. Edward Lewis reported upon the fossils of anthropoid apes found by the Yale North India, 1933, Expedition, and in his account expressed the opinion that two of the genera described "represent a much closer approximation to the Hominidae than other genera hitherto recorded." The two genera in question have been called respectively *Ramapithecus* and *Sugrivapithecus*, the former present in two species termed "*brevirostris*," and "*hariensis*," the latter in a single species named "*salmontanus*."

As finds of this nature are of direct and intense interest to Anthropology and a critical study of even the best casts is never entirely satisfactory, I endeavored, as soon as it became possible, to see the originals, which are preserved in the Department of Paleontology at the Peabody Museum of Yale University. With the kind permission of Professor Richard S. Lull, Director of the Museum, and the whole-hearted assistance of Doctor Malcolm R. Thorpe, Curator of Vertebrate Paleontology, I was enabled to examine the valuable remains to my satisfaction.

What I found may briefly be reported here. Attention, it appeared, needed to be concentrated on but two specimens, namely, the maxilla of *Ramapithecus brevirostris*, and the mandible of *Sugrivapithecus*. The fragment attributed to *R. hariensis* is too small and defective to give much information.

THE SPECIMENS.

The *Ramapithecus brevirostris* is represented by a somewhat defective young adult (or near adult) right maxilla with four excellently preserved and but slightly worn teeth (Pm^1, Pm^2, M^1, M^2), missing a portion of the premaxillary part of the alveolar process, most of the naso-frontal part, the whole zygomatic process, the alveolar process back of M^2, and a portion of the palatine process along the whole intermaxillary suture. Additionally, there is some crushing of the labial portion of the alveolus of the canine, and a crush-impression above the roots of the premolars externally.

Basing himself essentially on this specimen, Mr. Lewis has characterized the genus as follows:

"*Generic Characters.*—Simiidae (Hominidae?) in which the dentition parallels the hominid type in its broader aspects. The dental arcade of the upper jaw is parabolic, rather than U-shaped as in recent Simiidae, and hence the palate broadens posteriorly. The cheek-teeth of opposite sides of the jaw are more widely separated posteriorly than anteriorly, rather than approximately equidistant from M^2 to P^3. The face is very slightly prognathous, as contrasted with recent Simiidae. There are no diastemata in the dental series. The canine is small, not an antero-posteriorly elongated trenchant tusk but a hominid type with a transverse dimension exceeding the antero-posterior dimension.

"*Genotype.—Ramapithecus brevirostris*, sp. nov."

To the above it is necessary to take the following exceptions:

There is no satisfactory indication that the dental arch was materially parabolic or diverging backward instead of U-shaped; if the missing anterior portion of the alveolar process together with its median incisor be reconstructed, it will be seen that the subnasal prognathism, for a maxilla of these proportions and particular lowness, was quite marked; and, the canine, if the damage to its alveolus be discounted, was not small in relation to the jaw or the rest of the teeth, but of fair though not large proportions (mouth of alveolus 8.5 x 6 mm.).

Details. The maxilla is delicate and rather small. It must have belonged to a form appreciably smaller than the ordinary chimpanzee. It is in all probability that of a female individual.

The premaxillary protrusion, the nasal notch and the ridged and hollowed dorsal surface of the bone, and the curving roots of the I^1 and especially the Pm^1, are pithecoid in character, but the four teeth and particularly the anterior premolar come in general somewhat closer to human than those of any other known fossil or living anthropoid. But even with this anterior premolar the approximately triangular form of the crown, the relative lowness of the lingual cusp, the concavo-convex curve of the labial surface of the crown from the free edge of the tooth upward, and above all the low enamel cap, particularly lingually—are pithecoid features and keep the tooth well apart from the human.

The lowness of the enamel cap, particularly lingually, and that both absolutely as well as relatively to the size of the crown, is very apparent on all the teeth and exceeds that in any normal human. And the same is true of the relatively much higher (when looked at with the surface of the crowns facing the observer) line of the labial than that of the lingual cusps, and which can be attributed in but a slight degree to wear.

All these details are of taxonomic importance; and there are minutiae of crown and cusp conformation that could be added to this.[1] The whole leads to the following deductions:

The *Ramapithecus brevirostris* was a moderate-sized anthropoid ape, the upper denture of which reached, at least in the individual under examination, a greater general resemblance to the human than that of any other known fossil or living anthropoid ape. This particularly in Pm^1 and probably also the teeth anterior to this in the maxilla. But the teeth present show also a whole series of features that are pithecoid and distant from the human.

The maxilla itself, in the main, was pithecoid.

The genus, although in the upper denture, in general, nearer to man than are any of the Dryopitheci or the Australopithecus, cannot without further corroboration on the lower teeth, the mandible, and other parts of the skeleton, be legitimately established as that of a hominid, that is a form within the direct human ancestry.

Measurements of the Teeth[2] *and Maxilla.*

	Diameter antero-posterior along midaxes of tooth	Diameter transverse maximum at right angles to long axis of the tooth
M^1	9.6	11.–
M^2	10.–	ant. 1/2 11.8
Discounting facet for M^3	10.2	post. 1/2 10.9
Diameter antero-posterior of both molars in apposition	19.4	
Diameter antero-posterior of all four teeth	32.–	

Maxilla: Height of alveolar process, border of canine socket to lowest point on right nasal notch........................... 16 mm.

---

[1] In his description of the crowns Mr. Lewis has gone to more detail perhaps than was always safe. He tends to overestimate the wear; the M^2 shows no clear fovea anterior; he fails to mention that the posterior surface of the crown of M^2 presents a 6 × 3.5 mm. facet for M^3, which rather contradicts his opinion that there was to be expected a small M^3; the I^1 was distinctly larger than I^2; the insertion of the two incisors did not approach vertical and the alveolar prognathism is neither slight nor hominid; there was a well marked curve of spy to the denture; and the palate could not be called "high." But all these and a few other points are of no great weight diagnostically.

[2] For description of method and comparative data see author's papers cited under References.

It may be remarked here that in the casts of these remains, compared on the spot with the originals, all the measurements, due to shrinkage in the material, were found appreciably smaller.

The Sugrivapithecus.

The Sugrivapithecus—a hard name—is represented by the imperfect left corpus of a young adult (or nearly adult) and probably female lower jaw, with three perfect teeth (Pm_2, M_1, M_2) the whole roots of three others (C, Pm_1, M_3), and a small portion of the root of the lateral incisor.

In connection with this specimen Mr. Lewis has fallen, I am sorry to say, into a series of errors.[8] His characterization of the genus is as follows:

> "*Generic Characters.*—Simiidae (Hominidae?) in which the mandible is characterized by its divergent rami, well developed chin, laterally compressed and elongate cheek-teeth, hominid P_4, small canine and incisors, and the antero-posterior crowding of the dentition."

It will be well to take the above points seriatim.

"The mandible is characterized by its divergent rami." This statement is difficult to understand, for the only ramus that could have been present with the single fragment is almost wholly wanting. If, as is probable, the author meant the right and left sides of the corpus, then the statement is intelligible, but the specimen does not sustain it. Its comparison with other lower jaws of apes makes it in fact very probable that conditions as to divergence of the corpus and teeth were much the same as they are in other anthropoids.

There was "a well developed chin." This is an error. The author was misled by the lateral prominence on the labial surface of the bone due to the roots of the Pm_1 and the canine. Such a prominence, more or less developed, may be seen commonly in the mandibles of anthropoid apes. The lingual and the inferior aspects of the anterior portion of the mandible and, especially, the dorsal outline of the break which is situated somewhat to the left of the median line, show conclusively that there was no chin and that the conditions of the region resembled those in other anthropoid apes.

"Laterally compressed and elongate cheek-teeth." This is not a fortunate expression. The teeth are somewhat longer than broad, as is frequent in anthropoids and even in earlier or exceptional humans,[4] but they show not the slightest trace of any "lateral compression."

---

[8] Several of the apparent "errors" in Mr. Lewis' paper, to which Dr. Hrdlička calls attention, are merely differences in terminology as used by a vertebrate paleontologist and an anthropologist. Ed.

"Hominid P_4, small canine and incisors, and the antero-posterior crowding of the dentition." The teeth are in apposition, there are no diastema, but there is no crowding. The canine was both absolutely and relatively of fair size for a female individual, to which apparently the jaw belonged; its root, at the level of the mouth of the alveolus measures 9.2 x 7.1 mm. Finally, the "P_4" (Pm_2), with its large and deep retrocuspidal fossa (fovea portion) and its peculiar crown, is not at all hominid but anthropoid in type.

The jaw in fact has nothing 'hominid' about it outside of some relation to human in the crowns of the molars. It is thoroughly anthropoid. Its chin, as already stated, was of a well-defined receding anthropoid type. The dorsal bulge due to the large roots of the Pm_1 and the canine is thoroughly anthropoid. Between this bulge and the oblique ridge that marks the anterior labial boundary of the ramus, and due to them, there is a pronounced hollow, involving the upper four-fifths of the body, which is absent in man but occurs more or less marked in the mandibles of many anthropoid apes and lower primates. I like to call this the 'digital hollow' for when one takes hold of a whole mandible, the thumb and forefinger fit nicely into the depression on each side and the bone looks as if when more plastic it had been squeezed together by the pressure of the two fingers.

Beneath the root of Pm_2 there is a very small mental foramen, much smaller than usual in man, but more comparable to that in the anthropoid and lower primates.

The oblique ridge, already mentioned, is stout indeed, much more so than in any human jaw and even considerably more than in the other anthropoids.

Back of this ridge the bone—now the ascending ramus—is as if pinched tightly together, leaving both a marked dorsal and ventral hollow.

Lingually, there is no sign of the genial tubercles which characterize the human mandible. But there was the usual anthropoid inferior shelf with a good sized fossa above it.

The mylo-hyoid ridge is very faint, as usual in anthropoids and unlike in humans.

The height and strength of the body—excepting the oblique ridge—appear feminine. The body is fairly thick in the chin region, slender at Pm_2, gradually increasing to its greater thickness at M_3, and then rapidly petering to the thin lamella of the ramus.

---

[4] Compare data in my papers; also in Gregory and Hellman.

The teeth. The molars show a pronounced augmentation in size from M_1 back, which is entirely subhuman; it is even more marked in fact than in not a few individual anthropoid mandibles.

The lingual surface of the crown M_1 and especially M_2 shows deeper intercuspidal incisures than those usual in man, but as common in the anthropoid apes.

The Pm_1 is inserted decidedly obliquely, as in anthropoid and other apes, much more so than in humans. This is another important simian character presented by the specimen.

The enamel cap, particularly lingually, is lower than in man and like that in the anthropoids.

To conclude, it may be stated that the present specimen shows throughout the characteristics of an anthropoid jaw; that the only resemblance to human, and that not very close, is present in the crown-surfaces of the two molars; and that to associate the form the mandible represents with the hominid line would be utterly unjustifiable.

For the sake of greater completeness I shall add here the measurements which I obtained on the original:

Teeth[5]

	Diameter antero-posterior of crown, in median line	Diameter transverse maximum of the crown
M_1	11.5 mm.	9.– mm.
M_2	12.2	10.7
M_3	Socket shows tooth larger than M_2	
All 3 teeth 31.—		

Note: Teeth not worn. M_1 looks like deciduous last molar.

Mandible. Maximum thickness of chin part (as far as preserved) 13.6 mm.

Thickness of jaw	opposite middle of canine.......	13:6 mm.
	opposite anterior portion of Pm_2	11.9 mm.
	opposite middle of M_1..........	13.–
	opposite middle of M_2..........	16.0
	opposite middle of M_3..........	19.0

REFERENCES.

Brown, Barnum, W. K. Gregory and M. Hellman: On three incomplete anthropoid jaws from the Siwaliks, India. Am. Mus. Novitates, No. 130, 1924.

De Terra, H.: Preliminary report on the Yale North India expedition. Science, LXXVII, 497-500, 1933.

---

[5] See footnote under Ramapithecus.

Hrdlička, A.: The Piltdown jaw. Am. J. Phys. Anthrop., V, 337-347, 1922.

———.: Dimensions of the first and second lower molars, with their bearing on the Piltdown jaw and Man's phylogeny. Am. J. Phys. Anthrop., VI, 195-216, 1923.

———.: Variation in the dimensions of lower molars in Man and anthropoid apes. Am. J. Phys. Anthrop., VI, 423-438, 1923.

———.: New data on the teeth of Early Man and certain fossil European apes. Am. J. Phys. Anthrop., VI, 109-133, 1924.

Lewis, G. E.: Preliminary notice of new man-like apes from India. This Journal, XXVII, 161-179, 1934.

———.: Preliminary notice of a new genus of lemuroid from the Siwaliks. This Journal, XXVI, 134-138, 1933.

U. S. National Museum,
Washington, D. C.

GLACIAL AND INTERGLACIAL DEVELOPMENT OF CHITTENANGO FALLS STATE PARK IN CENTRAL NEW YORK

CHAUNCEY D. HOLMES.

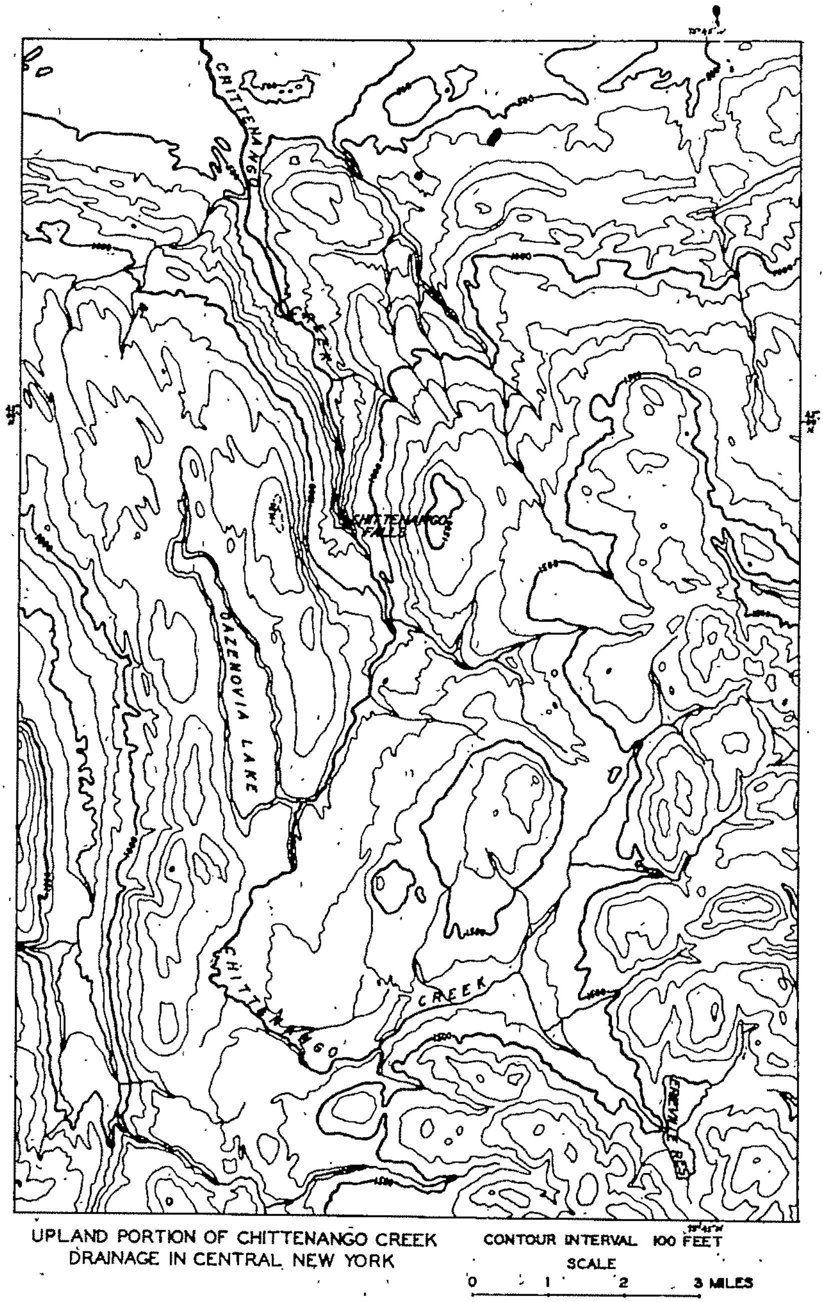
INTRODUCTION.

Drift-filled interglacial gorges have long been known from various localities in the southern Finger Lakes region of New York State, and ably interpreted by Tarr, Von Engeln, Rich and Filmer, and others. Similar evidence of interglacial erosion was noted at Chittenango Falls State Park in 1931 by the writer in company with Dr. Earl T. Apfel of the Geology staff at Syracuse University. Professor Apfel has kindly advised in the study of the area, and courteously assisted in the preparation of this paper.

DESCRIPTION AND INTERPRETATION.

Chittenango Creek drains nearly seventy-five square miles of territory at the northern margin of the Allegheny Plateau in central New York (Fig. 1). The last ten miles of its descent from the plateau lead through a narrow and picturesque valley. About midway in this valley the stream falls in a precipitous cascade over a series of massive limestone strata. It is a waterfall of exceptional beauty, 134 feet in height. A conspicuous ledge about halfway down breaks the continuity of the cascade, perhaps adding a bit to its attractiveness. This waterfall, known as Chittenango Falls, and its environs now constitutes one of the New York State Parks, and claims an increasing number of visitors each year.

Downstream from the waterfall, the limestone forms a moderately narrow gorge for about a quarter of a mile. Beyond this point the rock gorge is much wider and the cliff on the west side is concealed for a considerable distance by glacial drift which partly fills the valley. In a few places on the east side the stream is now cutting against shales which underlie the limestones; at other places the stream course is over an unknown thickness of drift filling beneath the valley floor. In many places, back from the floodplain, the limestone forms vertical cliffs of varying heights. A well developed moraine constricts the valley about three miles below the waterfall, and another moraine extends across the valley a



UPLAND PORTION OF CHITTENANGO CREEK
DRAINAGE IN CENTRAL NEW YORK

Fig. 1.

mile or more above the waterfall. These moraines are readily distinguishable on the U. S. G. S. topographic maps of the Chittenango and Cazenovia quadrangles, respectively.

Difference in erosional resistance offered by the several rock formations into which this valley is cut has provided the setting in which the interglacial evidence at this park has been preserved. The controlling topographic element is a series of massive limestone beds, about 175 feet in thickness. It includes the Manlius and Helderberg groups of this region, and a large part of the Onondaga formation. The gentle southward dip of the strata and the north-sloping stream gradient combine to bring the base of the limestone series to the bottom of the gorge in the vicinity of the park. Above the massive Onondaga beds, the character of the rock changes abruptly to the fissile black shales of the lower part of the Hamilton group.[1] Removal of these overlying shales by erosion has left a wide limestone terrace on the east side of the valley. This stripping may have been accomplished by glacial action or by normal subaërial erosion; or more probably it is the combined result of both. At any rate, stream diversion across this terrace in Pleistocene time led to the development of the interglacial gorge diagrammed in Fig. 2.

At least three stages of gorge development are displayed in the Chittenango Falls park. What appears to be the oldest one is buried under drift near the west side of the valley (Fig. 2, A-B). The rock gorge widens abruptly at this point, the limestone wall on the west side being completely hidden under the drift which forms the west side of the present gorge for some distance below. The outer margin of the rock terrace on the east side reveals a part of the moderate slope which led down into this ancient valley (Fig. 2, E-H). The lowest exposure of bedrock on this slope occurs in the bed of the small stream entering the present gorge at this point, and shows a decline of about forty feet below the rock terrace level fifty yards away. Except for this instance, no rock outcrops occur along this stream, though its bed is lower than the limestone terrace for a quarter of a mile upstream. The first road constructed through the valley utilized this break in the gorge wall to effect a passable grade from the lower to the higher level. The land surface above this buried gorge is quite rugged in places, due in part to erosion by tributaries of the small stream to which reference has already been made, and in part to depositional irregularities or to slumping following the melting of buried ice masses. The position of the upper end of this oldest gorge is not known, but it is probably at least a few hundred yards upstream from this point. Also its width is unknown because of the heavy drift cover. It may be inferred from the character of the upper part of its slope that it had been widened considerably and was therefore less steep-sided than the later rock gorges.

---

[1] Cooper, G. A., this Journal, 5th. ser., vol. 19, pp. 116-134, 214-236, 1930.

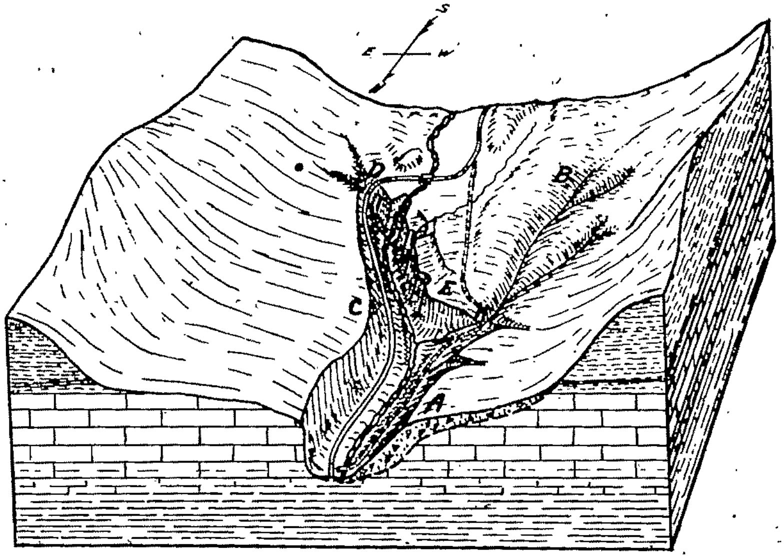


Fig. 2. Block diagram showing relative positions of the several gorges at Chittenango Falls State Park. Oldest gorge, A-B, drift-filled. Interglacial gorge, CE-D. Present highway shown in solid lines, abandoned highway in dashed lines.

The age of this earliest gorge may be glacial, preglacial, or interglacial; though the evidence seems to favor interglacial. Two prominent hills with over-steepened sides rise above the valley on either side of the park in such a manner as to indicate that a preglacial col existed between them. It is a situation of frequent occurrence in the adjacent Finger Lakes region, and excellently interpreted by Monnett.[2] If such were the case, the col may have been obliterated by glacial erosion, and a valley developed by the same means in the limestone between these hills. From a study of other comparable instances in which the circumstances for such glacial erosion seem equally favorable, and in which the underlying limestone was but slightly eroded, it seems more probable that the erosion of the limestone in this earliest gorge was accomplished by stream wear after glaciation had cut down the col to the limestone horizon and had shifted the divide farther south so as to increase the size of the drainage area. However, the varied direction of stream flow within this drainage basin as it is at present is doubtless the result of a complex history, in which preglacial or interglacial stream piracy may have had a part (see Fig. 1). For this reason, it seems best to regard an interglacial age for the oldest gorge at Chittenango Falls as only a tentative conclusion. Subsequent to its formation, it became completely filled with glacial drift.

---

[2] Monnett, V. E.: this Journal, 5th ser., vol. 8, pp. 33-53, 1924.

Following the disappearance of the glacier, whose deposits buried this first gorge, the interglacial Chittenango Creek flowed for a distance along the limestone terrace on the east side of its former channel, entering the latter at the location C-E, Fig. 2. In the ensuing interglacial time it eroded the gorge extending from this point southeastward for a little more than a quarter of a mile. The rock walls on either side of this second gorge show its nearly uniform width and steep-sided form. It narrows at the upper end (shown at D in Fig. 2) where two small ravines expose the approximate upstream limit. It is evident that the crest of the waterfall had receded faster than the base, resulting in a cascade much less steep than the present one. The size of this gorge, and its slight downstream widening, indicate that the interglacial stream must have been of about the same size as that of the present. At least it was no larger.

Subsequently, the region was again glaciated and this second gorge was filled with drift. Striae on the terrace indicate that ice movement was parallel to the major axis of the valley (nearly due N-S), and huge blocks of limestone were pushed into the gorge from the northeast side and incorporated into the till. The postglacial stream has only partially removed this bouldery till, so that the State Highway utilizes it in ascending to the terrace level. It is especially significant that the upper end of this gorge still retains its drift filling, since it shows the extent and character of interglacial stream activity.

In early postglacial time, the stream apparently flowed for a time over the rock surface on the southeast side of the interglacial gorge, sweeping away any drift which may have been there and producing a decidedly waterworn appearance on the ledges and low benches found on this side of the gorge. A semicircular notch indenting the southwest side near the lower end (near E, Fig. 2) marks a former position of the postglacial waterfall. No stream occupies it at present. Another notch, somewhat larger, occurs nearer the present site of the waterfall, where a small brook enters. This also seems to have been occupied by the main stream for a brief interval before it finally became established at its present location, in which the stream approaches the interglacial gorge at nearly right angles. This adjustment was evidently accomplished in a relatively brief time, and the third stage of gorge cutting was inaugurated. The length of this recent gorge is not more than 200 feet, and serves as a measure of postglacial time in this region.

The second gorge,—the only one here interpreted definitely as interglacial,—is about 8½ times the length of the postglacial gorge. Assuming a value of 20,000 years for postglacial time, and a similar rate of lengthening for each gorge, the interglacial time represented here would be 170,000 years. Although there is no definite proof that this time span was continuous, such an assumption is not at all unreasonable. Also, there is the possibility that the gorges interpreted as the first and second may be reversed in their order of age, though this is unlikely. But the fact of interglacial erosion is well established.

Regarding the rate of postglacial waterfall recession, it is probable that the first few tens of feet were accomplished at a rate more rapid than that of the present. At the start, the fall was apparently over a vertical cliff. The brink was, therefore, less supported, and hence more quickly eroded, than is now the case, where underlying strata project successively beyond those overlying. If this is true, the length of interglacial time may have been greater than that postulated, perhaps a total of 200,000 years. The tendency of the present waterfall seems to be toward a less abrupt form of cascade, due to more rapid recession at the brink than at the base. It will, therefore, approach the form of its interglacial predecessor.

SUMMARY.

Interglacial erosion at Chittenango Falls State Park in central New York is represented by a gorge about a quarter of a mile in length, cut in thickbedded limestone which forms a broad valley terrace. Its dimensions indicate a volume of water comparable to that of the present stream. Postglacial erosion has resulted in a similar gorge only 200 feet in length, branching from the interglacial gorge near its head. If the rate of interglacial erosion was the same as that of the present, the time required to develop the interglacial gorge would be 8½ times the length of postglacial time. Assuming the latter to be 20,000 years, an interglacial time of at least 170,000 years is indicated.

Topographic evidence from the upland immediately adjacent indicates that the channel along whose side the limestone terrace exists may also be interglacial in age, probably earlier than the one on the terrace. But the evidence seems not to be conclusive, and only a tentative interpretation is made.

Syracuse University,
Syracuse, N. Y.

OLIGORHYNCHIA, A NEW ORDC
BRACHIOPOD.

G. ARTHUR COOPEI

Not long after the publication of t *Salonia* by Cooper and Whitcomb,[1] Pı Yale University sent a few similar app me for comparison with *Salonia*. Alth are much older than *Salonia* the extern: genus is striking. The type of folding i in both genera and the details of the e to minute characters such as the faint the length of the ventral sulcus. On interior of Professor Schuchert's specir apparent that they had nothing whateve The latter is the earliest-known represe *Pentameridae* and as such is provided wi ventral valve and long, subparallel sept: None of these structures is possessed b which prove to be related to rhynchon pentameroids. Fortunately, one of I specimens is silicified. This specimen v matrix by the use of acid and revealed a interior except the position and size of proved impossible to separate the two val unusually large teeth in the ventral valve firmly. In the attempt to wedge the two of the dorsal valve broke away. The ir must be viewed from an antero-dorsal the most advantageous point from which the internal structures. The internal specimens to belong to a new genus w *rhynchia* in allusion to its small size.

All of the figured types are in the Sc brachiopods, Peabody Museum of Na paratypes, representing one of the speci in the United States National Museum, Schuchert.

It is a pleasure to acknowledge my g Schuchert for the privilege of describi interesting little shells.

---

[1] Jour. Wash. Acad. Sci., vol. 23, p. 500, figs. 1

Oligorhynchia, n. gen.

Shells small, triangular in outline, rhynchonelloid in appearance. The beak is erect, the foramen elliptical. The delthyrium is covered by a symphytium (?).

The dental plates are strong, divergent and extend to the floor of the valve. The teeth are unusually large and long.

Inside the dorsal valve there are slender and rather long brachial processes attached to stout, wing-like crural bases that are extended postero-ventrally into the opposite valve. These fit snugly against the teeth and dental plates (see Plate I, Figs. 2 and 13). The sockets are defined by fulcral plates. There is no median septum but there is a low ridge just in front of the cardinalia which corresponds to the sulcus at the posterior of the dorsal valve. There is no cardinal process.

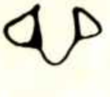
Genotype.—Oligorhynchia subplana Cooper, n. gen., n sp.

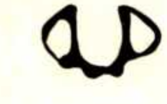
The structure of this shell is unlike that of any known rhynchonellids. Because of its early age it might be expected to have relationships with *Protorhyncha*, but such is not the case. *Protorhyncha* is unlike *Oligorhynchia* internally and externally. On the outside of the shell *Protorhyncha* is provided with numerous, rather fine and subequal ribs and the delthyrium is open. Internally the cardinalia are delicate, showing no such ponderous crural bases as *Oligorhynchia*. The new genus is unlike *Orthorhynchula* in having a closed delthyrium, no cardinal process and a completely different structure of the cardinalia.

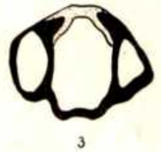
Oligorhynchia subplana, n. sp.

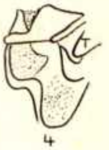
(Pl. I, Figs. 2, 8, 13, 14; Text Figs. 1-4.)

Shell small, triangular in outline and lenticular in profile. Valves subequal in depth, the dorsal valve having a slightly


1

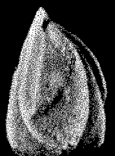

2


3

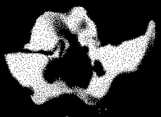

4

Figs. 1, 2, 3. Apical sections of the beak of an average specimen of *Oligorhynchia subplana*. 1 and 2 are of the ventral beak showing the strong dental plates; 3 shows the two valves, the stippled portion representing the dorsal valve. This view shows the position of the crural bases in relation to the dental plates.

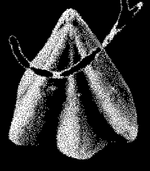
Fig. 4. Side view of the interior showing the large crural base and the crus extending from its base. All views about x 15.



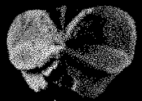
1



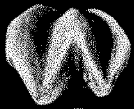
2



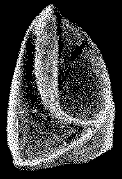
3



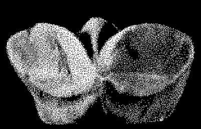
4



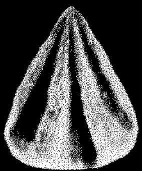
5



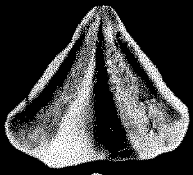
6



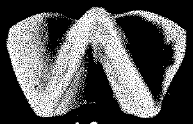
7



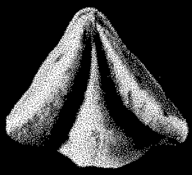
8



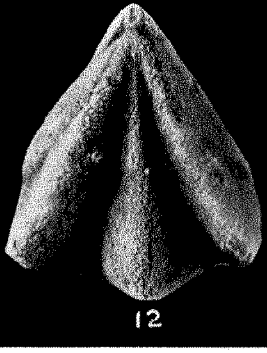
9



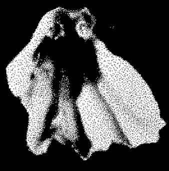
10



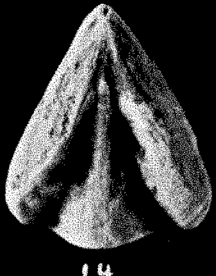
11



12



13



14

greater depth than the ventral valve. Lateral margins nearly straight to gently convex. Greatest width of the shell in the anterior quarter of the valves. Anterior margin subtruncate. Both valves strongly plicated and the whole surface marked by fine concentric growth lines.

The ventral valve is gently convex in lateral profile and a little more convex than the dorsal valve. The beak is erect, rather long and bluntly pointed. The symphytium (?) is convex. Beak ridges strong. There are four strong subangular plications gently curving laterally. They are divided centrally by a subangular, deep median sulcus. These plications unite at the posterior of the shell to form a smooth umbo. The inner pair of plications is the stronger and unites a little in front of the beak to form an elevated fold for a short distance. This merges posteriorly with the umbo. The outer plications are not so strong as the inner ones and meet the antero-lateral angles of the shell. Down the center of the median sulcus there is a fine, elevated ridge or costella.

The dorsal valve is flatly convex in profile and is marked by three strong subangular plications; there is a strong median plication which is depressed below the lateral plications forming the sides of the shell. The two lateral plications unite at

---

PLATE I.

Figs. 2, 8, 13 and 14. *Oligorhynchia subplana* Cooper, n. sp.

Fig. 8 is a ventral exterior showing the four strong plications and the faint median costella in the sulcus, x 4. Fig. 14 is the dorsal valve of the same individual, x 6, showing the beak and foramen. Ottosee formation, Luttrell, Tennessee. Fig. 2 is an internal view. The shell is so tilted that the observer is looking directly from the front into the apex of both valves. The dorsal valve is above, the ventral below. In the dorsal valve the crural bases are visible lying against the dental plates which were partially destroyed owing to poor silicification. Fig. 13 is the same specimen. The remnant of the dorsal valve (above) is clinging to the nearly complete ventral valve. The fulcral plate and crus are visible on the right side of the shell. On the left only the stub of the crus is visible. Both views x 6. Ottosee formation, Speers Ferry, Virginia.

Figs. 1, 3, 4, 5, 12. *Oligorhynchia subplana var. gibbosa* Cooper, n. var.

Figs. 1, 3, 4 and 5 are respectively side, dorsal, posterior and anterior views. Comparison with the views of *O. subplana* will show the more rudimentary lateral plication which gives the variety a more pentameral outline, all x 4. Fig. 12 is the same as fig. 3, but x 8. Ottosee, Luttrell, Tennessee.

Figs. 6, 7, 9, 10, 11. *Oligorhynchia angulata* Cooper, n. sp.

Respectively side, posterior, ventral, anterior and dorsal views of the same individual, all x 4, Ottosee formation, Luttrell, Tennessee, associated with *O. subplana*.

the rear of the shell where the umbo is quite smooth. The median plication does not reach the umbo; it dies out a little in front of the umbo, leaving a short but deep sulcus. Outside the two strong lateral plications on each side of the valve there is a low plication curving from the beak to the antero-lateral extremity.

The interior is as described for the genus.

Measurements taken from the holotype are as follows:

Length	Width	Thickness	Width of sulcus at front
5.5 mm.	4.5 mm.	2 mm.	1.7 mm.

Horizon and Locality.—*Chazy* (Ottosee), Speers Ferry, Virginia; Luttrell and Washburn, Tennessee.

Disposition of Types.—Holotype, Cat. No. S2251, Peabody Museum, Yale University. Paratypes, Cat. Nos. S2253-2257, in the same museum.

This species differs from *O. angulata*, n. sp., in its narrower outline, less angular folds and ornamentation. It resembles the variety *gibbosa* in its slenderer profile.

Oligorhynchia subplana var. *gibbosa*, n. var.

(Pl. I, Figs. 1, 3, 4, 5, 12.)

This variety differs from *subplana* in being thicker and somewhat narrower, and in having a more attenuate beak. The lateral plications are present on the ventral valve but not so strongly developed. The variety differs from *O. angulata* in being much narrower.

Measurements taken from the holotype are as follows:

Length	Width	Thickness
5 mm.	4.3 mm.	3 mm.

Horizon and Locality.—Chazy (Ottosee), Luttrell, Tennessee.

Disposition of Types.—Holotype, Cat. No. S2252, Peabody Museum, Yale University.

Oligorhynchia angulata, n. sp.

(Pl. I, Figs. 6, 7, 9-11.)

This species differs from *O. subplana* in being proportionally wider and thicker, and in having more angular plications.

On the ventral valve the median sulcus is very narrow for a short distance but the edges of the plications soon diverge by a gentle curve to make the sulcus extremely wide and deep. As in the former species, there is a faint median ridge or costella in the sulcus. In the dorsal valve the lateral slopes forming the outer sides of the shell are not marked by a low plication as in the former species and its variety.

Measurements are as follows:

Length	Width	Thickness	Width of sulcus at front
5.5 mm.	6 mm.	3 mm.	4 mm.

Horizon and Locality.—Chazy (Ottosee), Luttrell and Washburn, Tennessee.

Disposition of Types.—Cotypes, Cat. Nos. S2258-2259, Peabody Museum, Yale University.

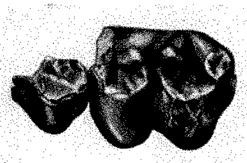
U. S. National Museum,
Washington, D. C.

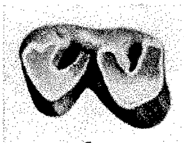
A MIDDLE EOCENE MAMMAL FROM BRITISH COLUMBIA.[1]

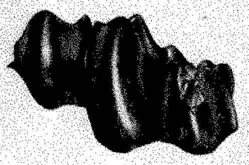
LORIS S. RUSSELL.

This paper records for the first time the occurrence of Tertiary Mammalia in the Province of British Columbia, Canada. The specimen to be described was found in the W. R. Wilson coal mine on the south bank of Similkameen river, at Princeton, British Columbia. It was turned over by Mr. C. Stubbs to Dr. B. R. MacKay, of the Geological Survey of Canada, who passed it on to the writer for determination.

The specimen (G.S.C. No. 8687) rests upon a small block of lignite, which is of dense texture, resembling a cannel coal. The basal portion of the teeth is surrounded by remnants of a thin clay parting. Pieces of coal were removed by the writer from between the cusps of the teeth. These teeth (Figs. 1, 2) may be identified as the first and second lower left molars, the first being represented only by the incomplete talonid, the


1


3


2

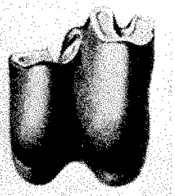

4

Fig. 1. *Trogosus minor* (Marsh)?, incomplete 1st and 2d lower left molars, G. S. C. No. 8687, crown view, x 1.

Fig. 2. The same, external view, x 1.

Fig. 3. *Trogosus minor* (Marsh), lower right molar, holotype, crown view, x 1 (after Marsh, 1876).

Fig. 4. The same, external view, x 1.

---

[1] Published with the permission of the Director, Geological Survey, Dept. of Mines, Ottawa, Canada.

second complete but for two small portions. These imperfections appear to be the result of careless collecting.

These teeth have the structure characteristic of the family Tillotheriidae. Comparing them with the type lower molar of *Trogosus minor* (Marsh)[2] (Figs. 3, 4) we note the same high crown, which tapers upward to the rather restricted triturating areas. Unfortunately, no unworn lower molars of a tillothere have been figured previously. The least worn figured specimen is this type lower molar of *Trogosus minor*. Compared with the Princeton specimen it shows the same U-shaped, rather than V-shaped, trigonid. In both fossils the metastylid has the same position and relative development. Most striking is the same peculiar bifurcation of the talonid crest at the posterior internal angle. The two small but distinct cusps that result from this may, perhaps, be called entoconid and hypoconulid, respectively. This feature appears to be characteristic of tillothere lower molars and is somewhat forecast in the ancestral Esthonychidae.

The principal difference between the Princeton tooth and the type of *Trogosus minor* is to be seen in the shape of the crown. In the latter specimen the talonid rises vertically, while in the Princeton tooth this portion has a distinct sweeping curve forward and upward. However, the size of the two teeth being so similar, and differences in cusp structure being non-evident, the British Columbian specimen is referred provisionally to *Trogosus minor*.

The order Tillodontia, to which this genus and species belongs, is a primitive group of uncertain affinities, appearing first in the Late Paleocene and apparently becoming extinct in the Eocene. The family Tillotheriidae was known previously only from the Bridger stage of Wyoming and the Tertiary (probably Shark River Eocene) of New Jersey. It appears highly probable, therefore, that this family is confined to the Middle Eocene, and the British Columbian specimen is dated accordingly.

The Princeton tillothere is of considerable interest in its relationship to the Tertiary stratigraphy of British Columbia. This province contains numerous isolated Tertiary deposits, apparently ranging in age from Paleocene to Miocene. The discovery of a mammalian fossil in this region opens up the possibility of detailed correlations in the manner so successful in the great plains and basins of the western United States.

---

[2] This Journal, ser. 3, vol. 2, p. 36, 1871; vol. 11, pl. 9, fig. 5, 1876.

GEOLOGICAL SURVEY,
DEPARTMENT OF MINES,
OTTAWA, CANADA.

DISCUSSION AND COMMUNICATION.

PEGMATITE MINERALS IN THE MARBLE AT FALLS VILLAGE, CONNECTICUT

In several[1] numbers of this Journal the writer has noted the fact that emanations from subjacent granites have affected the schist of northwestern Connecticut and have introduced tourmaline, quartz, and oligoclase into them, and that, though these materials necessarily passed upwards through a thick series of marbles before reaching the schist, they usually left no sign of their passage.

It is interesting, then, to find that the marble ledges at and below the falls at Falls Village show some small concentrations of pegmatite minerals.

A considerable area of limestone is exposed below the falls from which, except during periods of flood, all the water is diverted for power purposes. About one-quarter of a mile below the falls fragments of a former graphitic and siliceous schist layer in the limestone have weathered into relief. They are brownish-black and exhibit a high polish. Above and below these disrupted beds the marble contains a number of subhedral microcline crystals from one to four inches long and half as wide. The microcline holds a little quartz and about ten per cent oligoclase-albite as an irregular replacement microperthite.

Near the top of the cliff which forms the falls at high water, and about at its center, there are a number of two to four-inch long gash veins of smoky quartz with pyrite, pyrrhotite, and rare microcline. A few of these contain slender, broken crystals of green tourmaline, grass-green muscovite, and minute, reddish-black, striated crystals of rutile. Near the base of the spillway, at the head of the flume, there is another concentration of green muscovite between the ordinary medium-grained marble and a coarse-grained, recrystallized marble. The microscope reveals a little quartz, microcline, and rutile with the mica.

The total quantity of pegmatitic materials found here is very small. It is important only because of the rarity of such minerals in the marble.

Another indication of the effect of the granitic emanations can be seen in an eight-inch thick bed of silicated marble at the base of the falls on the west. This impure limestone was metamorphosed to diopside, scapolite, phlogopite, tremolite, and titanite, in the order of their importance, probably at the time when the original limestone was recrystallized to marble. It was then crushed and partly replaced by microcline and quartz. The latter cut across the foliation planes determined by the earlier formed minerals and replace the minerals themselves.

---

[1] May, 1931; January, 1932; May, 1933.

Another marble belt, that is probably the same age, and contains pegmatite minerals, forms the valley at the south of Cornwall Hollow, a few miles east of Falls Village. The marble is exposed only in a number of road cuts and is very impure. It contains diopside, titanite, tremolite, quartz, and some microcline. Brownish-green tourmaline is present in several places and fine dikes or veins of quartz and pegmatite are not uncommon.

WILLIAM AGAR.

COLUMBIA UNIVERSITY,
NEW YORK CITY.

SCIENTIFIC INTELLIGENCE.

CHEMISTRY AND PHYSICS.

An Introduction to Quantum Theory; by G. TEMPLE. Pp. 196. New York, 1934 (D. Van Nostrand Co., $3.75).—Dr. Temple's numerous papers on quantum theory qualify him particularly well to become the author of a book designed to introduce this important subject to students of physics and chemistry. The emphasis of his approach to quantum theory is on the fusion into a single dualistic theory of the monistic particle and wave theories of classical physics. He shows the necessity for the dualistic interpretation first in the case of photons and then in the case of material particles, developing the theory for the two classes of entities side by side as he progresses further into the subject. He treats the quantum theory both from the point of view of wave mechanics and from that of matrix mechanics. A number of simple problems, such as the simple harmonic oscillator, linear potential barriers, are solved by wave mechanical methods, and others, such as the hydrogen atom, are treated by matrix methods. The last two chapters are devoted to the relativistic wave equation and the spinning electron.

In his treatment of quantum theory the author uses hydrodynamical analogies very freely; perhaps too freely to suit the taste of most expositors of the theory. Occasionally he runs the risk of giving the reader wrong impressions by his effort to be realistic. Thus, in his discussion of the refraction of photons on page 16, he hails the reconciliation of the Newtonian particle theory of light with the wave theory which is afforded by the de Broglie equation. The reader who takes his remarks too literally, however, cannot fail to wonder how he harmonizes his point of view with the results of the famous experiments performed by Fizeau and Foucault on the velocity of light in water as long ago as 1850. For it is difficult to believe that these experimenters were measuring anything else than the speed of photons in an optically dense medium.

The book is written clearly and concisely, and should prove useful to those desiring a brief introduction to the essential features of the quantum theory. LEIGH PAGE.

The Reaction between Hydrogen and Oxygen; by C. N. HINSHELWOOD and A. T. WILLIAMSON. Pp. 108; 7 figs. Oxford, 1934 (The Oxford University Press, 114 Fifth Avenue, New York, $3.25).—One of the most thoroughly studied, and one of the most fundamental reactions in chemistry is that between hydrogen and oxygen. This book covers all the work bearing on the subject which has been published up to the time of printing which was early 1934. The catalytic, the photo-chemical, the purely thermal reaction at high and low pressures are all included, and what seems to the authors to be the most reasonable conclusion has been drawn in each case, though this conclusion may not be that in the original work.

The book fulfills a need in compiling the extensive experimental data, and is of general interest since it shows the various methods which may be used to study a gas reaction and gives a practical demonstration of the application of modern physical theory to the several types of reaction.

That the subject is by no means closed is shown by the appearance (Zs. physik. Chem. **170A**, 1, 1934) of a paper tending to oppose some of the conclusions drawn in the monograph.

JOHN E. VANCE.

CHEMICAL RESULTS OF THE GERMAN DEEP-SEA EXPEDITION OF 1925-27.*

This volume contains the first portion of the chemical results obtained during the German Atlantic deep sea expedition of 1925-1927. The data given cover most of the Southern Atlantic between latitudes 20° N. and 70° S. In all, 17,475 chemical analyses were made. Of these there were 6549 of hydrogen-ion concentration, or pH, 384 of carbon dioxide tension, 354 of titration alkalinity, 6577 of dissolved oxygen, and 3611 of dissolved inorganic phosphate. In addition 1555 samples were taken for gold analysis. Volume VIII deals more especially with the pH, carbon dioxide tension, and titration alkalinity of the sea water encountered and is divided into three parts.

The first part contains descriptions of the chemical laboratory and the method of work. It also contains the data for the hydrogen-ion concentration, phosphate, and oxygen, as well as a description of the analytical methods used to determine these quantities.

The titration alkalinity and its relationship to the dissolved calcium carbonate is taken up in the second part. A knowledge of the solubility of calcium carbonate in sea water is of importance in unearthing the origin and method of formation of the red clay and the various oozes. Over one-half of the bottom of the oceans is covered by these sediments. Because of their extensive and uniform distribution, the conclusion is almost inescapable that they are derived in some way from the sea water itself. Therefore, two sets of studies were made. The first involves the factors which determine the saturation of the sea water by calcium carbonate. These are hydrogen-ion concentration, carbon dioxide tension, temperature, and hydrostatic pressure. The second involves an examination of the changes produced in the chemical and physical properties of sea water when calcium carbonate is dissolved in it or precipitated from it.

---

* Wissenschaftliche Ergebnisse der deutschen atlantischen Expedition auf dem Forschungs- und Vermessungschiff "Meteor" 1925-1927. Edited by Albert Defant. Vol. VIII. Das chemische Beobachtungsmaterial und seine Gewinnung. Kalziumkarbonat- und Kohlensauregehalt des Meerwassers; by Hermann Wattenberg. Pp. ix, 333; 2 pls.; 43 text figs.; 27 graphical charts bound in separate cover. Berlin & Leipzig, 1933 (Walter de Gruyter and Co.).

The titration alkalinity, or the amount of strong acid required to displace the weak acids (chiefly carbonic) present, is taken as a measure of the dissolved calcium carbonate. This is justified because there are approximately five times as many chemical equivalents of calcium present as of carbon dioxide. Furthermore, calcium carbonate is by far the most insoluble salt present in sea water and thus is the first to separate. It is shown that normal sea water is at, or near, the saturation point for calcium carbonate. The titration alkalinity represents very nearly what Dittmar called "the potential carbonate of lime."

Of the alkalinity determinations, 64 were on the surface, 234 on deep, and 56 on bottom water. The alkalinity-chlorinity ratio, which is termed the "specific alkalinity," shows a minimum at about 100 meters depth; in the intermediate depths it is constant but near the bottom it increases greatly, the increase being greater the deeper the water. The variation in concentration of calcium carbonate thus shown is sufficiently great to disturb the ordinary relationship of chlorinity to density. Variations in the second decimal place in O'_t are detectable. The term "specific alkalinity," as used, is objectionable. The alkalinity is expressed in milliequivalents *per liter* and the chlorinity in grams *per kilogram*. The value obtained for their ratio are thus not strictly comparable.

The work on the solubility of calcium carbonate in sea water, under various conditions, is perhaps the most detailed and accurate yet done. Tables and equations are worked out for the variation in the solubility with salinity, with temperature, with carbonate dioxide tension, with pH, and with hydrostatic pressure.

It was found that surface waters are generally supersaturated with calcium carbonate. This is especially true in the tropical regions. The deep waters all show unsaturation which in part is brought about by the action of hydrostatic pressure upon carbonic acid. This unsaturation is by no means uniform. Over the bottom covered by red clay, which is relatively poor in calcium carbonate, the unsaturation may be as much as ten per cent; over bottoms covered by the Globigerina slimes, which are rich in lime, the unsaturation seldom reaches two per cent.

The third part of the volume deals with the pH and carbon dioxide tension of the water. These factors play an important part not only in the buffer mechanism of the sea, which to a large extent regulates the carbon dioxide content of the air as well as life conditions in the sea but also in such geologic processes as the dolomitisation of the corals and the deposition of the clays and sediments containing lime.

The seasonal variation in pH is restricted to a relatively thin surface layer in the middle and high latitudes. Near the equator it is practically nil. The variation in carbon dioxide tension is not so restricted. In the tropics, a layer of water rich in free carbon dioxide separates the light, warm surface water from deep water also poor in carbon dioxide. This is true only in the summer in the higher latitudes. This layer is broken up in the winter by the sinking of the cold surface waters.

Considerable information on the circulation and origin of the Atlantic waters is drawn from the pH and carbon dioxide data.

This volume may be regarded a major contribution to the study of the science of the sea. It is of marked interest to the general oceanographer and particularly to those interested in the physical, chemical and geological aspects of oceanography.

THOMAS G. THOMPSON.

The Practice of Absorption Spectrophotometry; by F. TWYMAN and C. B. ALLSOP. 2d edition. Pp. 144; 46 illustrations. London, 1934 (Adam Hilger, Ltd., 12s. 6d.).—A very considerable increase in interest in the subject of spectroscopic analysis is occurring at the present time. For in all branches of applied chemistry the importance of minute traces (as little as 1 part in 10^8) of various elements and compounds is being recognized. With the aid of the spectrograph these can be detected quickly and, under controlled conditions, quantitatively.

The first part of this volume contains an introduction to the theory of absorption spectra and an account of various typical applications of absorption spectroscopy. One can heartily endorse the recommendation that for the sake of uniformity all workers in this field adopt the nomenclature set out in the International Critical Tables of 1929. In Part II the technique required in photometric measurements of absorption is described and explained. The senior author is himself responsible for the design of many pieces of apparatus which facilitate these measurements. This book should be of value to all workers in absorption spectroscopy.

WILLIAM W. WATSON.

The World Around Us; by SAMUEL R. POWERS, ELSIE F. NEUNER and HERBERT B. BRUNER. Pp. xix, 471; 182 figs., frontispiece in color. Boston, 1934 (Ginn and Co., $1.20).—The authors, respectively professor of natural science, supervisor of natural science in secondary schools, and professor of education, have collaborated in writing this survey of science for use in junior high schools. While it is especially difficult to judge the effectiveness of this type of text-book without an actual trial, it is felt that this volume should prove very successful. It has been thoughtfully and carefully written, with the recommendations (1932) of the National Society for the Study of Education in mind. The subject is developed in units, by chapters, with frequent summaries, questions, and suggestions, not only for outside reading but also for "things to see and do." Appended is a list of reading material and a glossary of scientific terms. A. T. W.

Vorträge der Deutschen Physikalischen Gesellschaft, der Deutschen Gesellschaft für technische Physik, und der Heinrich-Hertz-Gesellschaft zur Förderung des Funkwesens. Pp. 90; 179 figs., 5 tables. Leipzig, 1933 (Johann Ambrosius Barth, Leipzig, RM. 9).—These proceedings cover the program of the ninth *Deutschen Physiker- und Mathematikertag* held in Würzburg, 1933. After an opening article by Professor Stark on organization of physical research this number presents a list of papers, chiefly on the technique of experiments in electricity and magnetism, with a few articles on acoustics, mechanics, and optics. The papers number twenty-four in all. A. T. W.

Ergebnisse der Exakten Naturwissenschaften, Vol. 12. Pp. 304; 107 figs. Berlin, 1933 (Julius Springer, 24 RM.; 25.40 RM. bound).—This volume contains six articles of which the following three will be found valuable for their comprehensive treatment of the subjects presented: Kohlschütter: *Spektroskopische Parallaxenforschung*; Tomaschek: *Die Messungen der zeitlichen Anderungen der Schwerkraft*; Farkas: *Uber Para- und Orthowasserstoff.* A. T. W.

The Mystery of the Atom; by H. A. Wilson. Pp. 145; 40 figs. New York, 1934 (D. Van Nostrand Co., $2.50).—The author of this book, a physicist of outstanding reputation, here provides an up-to-date account of the rise of modern physics with its novel developments concerning the fundamental concepts and laws of nature. After an introductory chapter on the ideas of matter and electricity held in the nineteenth century, the major part of the book is devoted to the progress of knowledge concerning the ultimate particles of matter, the structure of atoms and the nature of radiation. The concluding chapters take up cosmic rays and relativity, with a very brief touch of philosophy at the conclusion. The telling is simple and matter-of-fact. The more formal or lengthy proofs or demonstrations are given in ten appendices at the end of the volume. Elementary students of physics especially, in schools and colleges, should find the book excellent for side-reading in connection with topics in modern physics. The lay reader, without some knowledge and natural interest in physics, may not be attracted.

A. T. W.

College Physical Science; by PAUL MCCORKLE and J. ARTHUR LEWIS. Pp. 327; 153 figs. Philadelphia, 1934 (P. Blakiston's Son and Co., $2.00).—This text is intended for an orientation course in physical science and aims to present a survey of the subject which shall be valuable to students beginning college whether they plan to continue in science or not. Astronomy, geology, chemistry and physics are presented in such a way as to provide a general picture of the world as we know it and of man's uses of nature. Following each chapter are references, reference topics, problems, and experiments. The book closes with a brief account of recent discoveries and applications in physics.

A. T. W.

Colour Science, by WILHELM OSTWALD; translated by J. SCOTT TAYLOR. Two volumes: Part I, pp. 141, 21 figs., 4 color pls.; Part II,, pp. 173, 18 figs., 2 pls. London, 1934 (Winsor and Newton, Ltd., Part I, $5.00, Part II, $3.75).—These two small volumes complete the publication of the English translation of *Farbkunde* (1923), the original work by Dr. Ostwald, Nobel laureate in 1909. The books are admirably produced, especial pains having been taken with the color plates which are beautifully reproduced. The work is intended to provide handbooks for advanced students of color in the fields of education, art and industry. The author presents the subject from many angles. Part I deals with color theory and color standardization, in which a logical attempt is made to work out a thorough-going and consistent theory and to provide adequate means for color standardization. Part II concerns applied color science and discusses color measurement, the physics, the chemistry and the psychology of color. The writer and the translator have done a remarkable piece of work. The books are authentic, original and well-written, and should be highly valued by students and workers in this field.

A. T. W.

GEOLOGY AND MINERALOGY.

Traité de Géodésie; by Captain P. TARDI. Pp. xxx, 732 in 2 "fasicules"; 176 figs. Paris, 1934 (Gauthier-Villars, 150 francs). —The preface by Gen. G. Perrier explains the origin of this book. The stock of Francoeur's *Geodesy*, originally published in 1835 and but slightly changed in successive revisions became exhausted and the question arose as to whether the book should be revised or replaced by a new treatise. Because of the changes, one might well say the revolutions, that have occurred in geodesy, the decision was in favor of the latter course. Captain Tardi is well qualified by training and experience to start afresh. His book is in some respects like standard American treatises on geodesy. Like them it gives very practical details on the manipulation of instruments; it goes somewhat more deeply into theoretical matters but nothing like so deeply as Helmert. Two especially noteworthy differences are the space given to plane coördinates of geodetic points, a subject likely to become of great interest to American surveyors in the very near future; also, the attention devoted to physical geodesy, that is, to geodesy as a branch of geophysics. As soon as the geodesist tries to interpret and explain his results he becomes a geophysicist; this has been true from the beginning, long before the word geophysics was in current use. It is especially true to-day, and it is probable that future American textbooks will be obliged to give more attention to the geophysical aspect of geodesy. In the use that has already been made of the book at the Coast and Geodetic Survey a few misprints, mostly unimportant, have been noted. W. D. L.

The Geology of the Country between Springs and Bethal. An Explanation of Sheet No. 51 (Bethal); by F. A. Venter. With a chapter on Underground Water Supplies by H. F. Frommurze. Pp. 87; 3 text figs.; 3 pls., and a colored map (22 x 33 in.). Union of South Africa Geological Survey. Pretoria, 1934.—The Bethal Sheet covers an area of about 2,000 square miles in southern Transvaal, a little east of Johannesburg. It lies near the northern edge of the vast Karoo basin and is mostly occupied by the coal-bearing Ecca series of the lower part of the Karoo System and the associated dolorite. The pre-Cambrian rocks of the Johannesburg region extend a short distance into the western part of the area.

The text includes a summary description of the stratigraphy and a brief account of the economic resources and groundwater. The map is on a scale of 2.35 miles per inch. C. O. D.

Carte Géologique de l'Angola. Notice explicative; by F. Mouta and H. O'Donnell. Portuguese Republic Ministry of Colonies, Colony of Angola. Pp. 87; 12 plates and colored map (28 x 32 in.). Lisbon, 1933.—This important publication presents the first systematic treatment of the geology of Angola as a whole. The colored geologic map, on a scale of 1:2,000,000, shows 22 formational units and the text discusses briefly their stratigraphic relations.

A great pre-Cambrian complex forms most of the western half of the colony. It includes three distinct systems of metamorphosed sedimentary strata and a variety of igneous intrusives.

The Karoo system, which occupies a large area in northeastern Angola, includes the next youngest formations. It has a basal conglomerate of undoubted glacial origin, followed by shales and standstone with zones of fossil fish, plants, and Estheria.

Cretaceous formations (Apatian (?), Albian and Senonian) are limited to small areas along the coast where they overlap the pre-Cambrian complex. Tertiary formations are likewise limited to small areas near the coast, though the Eocene, Oligocene, Miocene, and Pliocene are all represented. Recent alluvium covers a large area in the southeastern part of the colony.

C. O. D.

Tertiary Faunas: Volume II, *The Sequence of Tertiary Faunas*; by A. MORLEY DAVIES. Pp. 252; 28 figs., 1 map. London, 1934 (Thomas Murby & Co., 15d. net).—This compact synthesis of the Tertiary faunas of the world was stimulated primarily by the needs of the oil-field stratigraphers, but it is packed with interest for all students of the Tertiary formations. It falls naturally into three divisions.

Chapter 1, devoted to geographical distribution of animal life, defines the modern zoogeographic provinces and points out in considerable detail the genera distinctive of each. Chapter 2, on the geological interpretation of fossils, discusses the relation of faunal to lithologic facies and the use of fossils in correlation. This is the most stimulating section of the book and, unfortunately, the briefest. In the remaining chapters, devoted to a synopsis of the successive Tertiary faunas, the paleogeography and the larger stratigraphic relations are necessarily introduced as a background giving meaning to the faunal differentiation.

Faced with the very difficult task of condensing so vast a subject into one small volume, the author has happily worked in bold strokes presenting important generalization stripped of detail, but fortified by copious bibliographic references. It seems almost ungrateful to call attention to an oversight in a work of this scope, but the conception of the cycle of sedimentation (p. 53) should not be credited to Rutot (1883) but to Newberry, who nine years earlier had made this the subject of an address before the American Association for the Advancement of Science. C. O. D.

On the Internal Structure of some Mesozoic Brachiopoda; by HELEN M. MUIR-WOOD. Philos. Trans. Roy. Soc. London, ser. B, vol. 223, pp. 511-567, pls. 62-63, 14 text figs., 1934.—It has long been known to some of us that most Mesozoic brachiopods, and most of the rostrate Paleozoic ones as well, can not be determined either specifically or generically from their original descriptions and illustrations. This is because authors as a rule describe only the external characters of their species; even when the separated valves of rostrate shells are found, as occurs rarely, they do not take the time to determine the internal characters by any one of the several known methods. At the present time, Miss Muir-Wood says, "less than half of the Mesozoic Brachiopods are specifically determinable, and little or nothing is known of their internal structure, their mutual relationship, or their evolution" (pp. 511-512). Moreover, similarity of external form appears over and over again in all the large families of brachiopods, and even the author of the term homoeomorphy was not able to separate all the homoeomorphs before him, since the internal shell characters could not be determined in all cases.

The author of the paper under review has applied the old methods and invented new ones, and has tried these various means of study on seven common Mesozoic species of as many different genera (including *Digonella*, nov.). All the characters of these seven genera, both external and internal, are here described and illustrated, with the result that the more important characteristics are found to occur on the inside of the dorsal valve. New morphologic structures, such as accessory sockets, denticulum, denticular cavity, and septalial plates, have been found. Complete brachial supports have been dissected out and beautifully illustrated in four genera. Only along these lines of preparation of material and its study will we ever attain a demonstrable genetic classification of the rostrate shells, whether of the Mesozoic or of the Paleozoic. We congratulate the author on her success as a pathfinder. C. S.

Les Brachiopodes du Dinantien de la Belgique, Premier Volume, Atremata, Neotremata, Protremata (pars); by F. Demanet. Mém. Mus. Roy. d'Hist. Nat. de Belgique, No. 61, pp. 1-116, 10 pls., 17 text figs., 1934.—In this monograph the author redescribes the old, and names the new brachiopods of the Lower Carboniferous of Belgium. He recognizes 15 genera (2 Atremata, 4 Neotremata, and 9 Protremata), and 39 species and varieties, 16 of which are new. The fossils are illustrated by excellent photogravures. The next volume will treat of the rest of the Protremata (*Productus*, etc.) and the Telotremata. C. S.

The Cambrian Area of Rushton (*Shropshire*); by E. S. Cobbold and R. W. Pocock. Philos. Trans. Roy. Soc. London, ser. B, vol. 223, pp. 305-409, 1934.—This monograph presents the Cambrian succession of the Rushton area, thoroughly worked out, with descriptions of the various faunas. Of species there are 101, 86 of which are specifically named, and 29 are new. There are two new genera: *Rushtonia*, an annelid; and *Agaso*, a subgenus of the trilobite *Liostracus*. The upper Cambrian has six named zones, the Middle Cambrian five, and the Lower Cambrian six. The work should be of much value to all students of Cambrian faunas. C. S.

Problems of Petroleum Geology: A Sequel to Structure of typical American Oil Fields; edited by W. E. WRATHER and F. H. LAHEE. Pp. xii, 1073; 200 illus. The American Association of Petroleum Geologists, Tulsa, Okla., 1934; Thomas Murby, London, price $6.00.—This impressive volume, the Sidney Powers Memorial Volume, is fittingly dedicated to the late Sidney Powers. Under his direction the first two volumes on Structure of Typical American Oil Fields were prepared, and he was engaged at the time of his death in assembling the materials for this book. It consists of forty-three papers by forty-seven authors and is designed "to review, modify and, if possible, to clarify our ideas with regard to the fundamental concepts of oil geology." This purpose has been admirably achieved.

This book proves clearly that petroleum geology has attained maturity and is making notable contributions to the principles of pure geology. It is in seven parts. A brief enumeration of the titles of these parts demonstrates the broad scope of the book. Part I, History, gives the historical development of the structural theory of the accumulation of oil and gas. We are told on page 20 that the important rôle of structure in the accumulation of both gas and oil has long since been proved. Why, therefore, refer to this principle as the structural "theory"? Part II is on the origin and evolution of petroleum; Part III discusses the migration and accumulation of petroleum; Part IV treats of the relation of accumulation to structure; Part V discusses porosity, permeability, and compaction; Part VI deals with oil-field waters; and Part VII with subsurface temperature gradients. Each of these sections is preceded by a short introduction in which attention is directed to the unsolved problems. Sincere congratulations are due to the editors for carrying out so successfully this great work. ADOLPH KNOPF.

Historical Geology; by WALTER A. VER WIEBE. Pp. 162; 206 figs. (Photolithoprint, paper covers). Ann Arbor, Michigan, 1934 (Edwards Bros.).—Recently several textbooks, such as Wills' *Physiographical Evolution of Britain* and Snider's *Earth History*, have departed from the conventional chronologic order in presenting geologic history. Ver Wiebe's volume departs from convention so far that it exactly reverses the usual treatment, beginning with the Recent and working back by Periods to the pre-Cambrian, and winding up with the origin of the Earth. The author finds his justification in the old pedagogical principle of proceeding from the known to the unknown. No one will deny the soundness of the principle, although the reviewer believes that the disadvantages of looking at geologic history "hind-end foremost" outweigh the advantage of beginning an elementary study with the best-preserved part of the record. Whatever the merits of the order of presentation, the volume offers a surprisingly large amount of information, including many recent data, presented in condensed form. The author has particularly stressed the origin of the striking natural features of the National Parks, and has included many block diagrams showing the present natural regions of the United States. He has made an effort to reduce the relative importance of Appalachian Paleozoic stratigraphy and the pre-Cambrian of the Canadian shield, in order that western areas may receive greater emphasis. R. F. F.

A Laboratory Manual of Physical and Historical Geology; by KIRTLEY F. MATHER and CHALMER J. ROY. Pp. 302; 46 figs., 20 plates, and folded map. New York, 1934 (D. Appleton-Century Co., $2.50).—This is one of the most complete and comprehensive laboratory manuals that have come to the reviewer's attention. The authors stress the opportunity afforded by laboratory study to train the student in independent scientific thinking, and the exercises appear to have been carefully thought out for this purpose. The Manual is arranged for use in conjunction with the Snider textbook *Earth History*, but numerous references to standard texts are given. The exercises cover minerals, rocks, fossils, topographic-map studies of the geologic processes, and geologic-map studies of unit regions in North America. Many of them are preceded by descriptive discussions in condensed textbook style, and most are illustrated with good black-and-white maps, sections, and other diagrams. Blank sheets and other forms are included with each exercise, and are arranged so that they can be torn out, handed in, and re-bound in the manual.

Teachers wishing a very comprehensive manual suitable for a thoroughgoing introductory course will find this an excellent book. R. F. F.

United States Bureau of Mines; DR. SCOTT TURNER, Director.—Recent publications by the Bureau of Mines are noted in the following list.* (See earlier, vol. **25**, pp. 188, 189.)

MINERAL RESOURCES of the United States for 1930, 1931 (bound volumes); by O. A. KIESSLING, Chief Economist.—1930. Part I, Metals. Pp. 1142. Part II, Non-metals. Pp. 876. Price $1.50 each, in cloth.—1931. Part I, Metals. Pp. 710 ($1.50). Part II, Non-metals. Pp. 675 ($1.00).

MINERALS YEARBOOK, 1934.—Contains the statistical information and economic discussions of mining given in various publications including the annual "Mineral Resources of the U. S.". It embraces 1154 pages in 72 chapters, with 106 illustrations. 6,300 copies have been printed. Price $1.75. Many chapters of the

---

* Publications may be obtained from the Superintendent of Documents, Government Printing Office. Remittance of total cost to be made by cash, or money order.

Minerals Yearbook of 1932-33 have been distributed; also of the Statistical Appendix.

BULLETINS.—No. 351. Mining petroleum by underground methods; by GEORGE S. RICE. Study of methods used in France and Germany with possible application to depleted oil-field under American conditions. (15 cts.)

No. 368. Static electricity in nature and industry; by PAUL G. GUEST. (10 cts.)

No. 369. Explosion tests in Pittsburgh coal dust in the experimental mine, 1925-1932; by G. S. RICE et als. (5 cts.)

No. 370. Iron oxide mineral pigments of the United States; by HEWITT WILSON et als. (15 cts.)

No. 371. Data on theoretical metallurgy. II. High temperature specific heat equations for inorganic substances; by K. K. KELLY. (10 cts.)

No. 372. Accounting system and office management for medium size metal mines; by A. E. KELLER. (10 cts.)

Nos. 373, 380. Coal mine accidents in the U. S.; by W. W. ADAMS et als. No. 373 for 1931, No. 380 for 1932. (10 cts. each.)

Nos. 374, 377. Metal mine accidents in the U. S.; by W. W. ADAMS. No. 374 for 1931; No. 377, 1932. (5 cts. each.)

Nos. 375, 376. Quarry accidents in the U. S. No. 375 for 1931; No. 376, 1932; by W. W. ADAMS. (5 cts. each.)

No. 378. Underfeed combustion, effect of preheat and distribution of ash in fuel beds; by P. NICHOLLS. (10 cts.)

ECONOMIC PAPER.—No. 16. Potash; by BERTRAND L. JOHNSON.

TECHNICAL PAPERS.—Nos. 548, 551, 554. (10 cts. each.) Also 555, 557, 559. (5 cts. each.)

The Monthly Lists also note the Reports and Information Circulars in various lines. These are in part free.

MISCELLANEOUS SCIENTIFIC INTELLIGENCE.

The Building of the Roman Aqueducts; by ESTHER BOISE VAN DEMAN. Carnegie Institution of Washington, Publication No. 423, 1934. Pp. xi, 440; frontispiece, 59 pls., 49 text cuts.—No one could be better fitted to write about Roman aqueducts than is Miss Van Deman, for she is our greatest authority on dating the construction of brick and concrete walls of Rome. The volume deals not only with a detailed description of the existing remains of the eleven aqueducts of Rome, but also with their structural development and methods of construction. The author herself visited the Campagna and the distant hills and valleys in order to study the sources of the water supply.

The first chapter gives a rapid survey of the builders of the aqueducts, and the structural history of each in chronological order. Here the author explains the gradual changes in the type of structure from the underground type of channel and its roof construction to the full development of the Aqua Claudia and Anio Novus with their long line of lofty arches across the Campagna, their deep-laid tunnels and stupendous bridges. Even the best built aqueducts needed frequent repairs. Although Hadrian did not build new channels, all the important aqueducts and their branches show traces of his care.

Chapters II to XII give an accurate description of the eleven aqueducts of Rome taking the literary evidence, especially Frontinus and the epigraphical references, into account. Each chapter begins with the history of the aqueduct under consideration, its source, collecting basin or reservoir; its length, both underground and above ground; its capacity or volume of water; its later branches; the extent of its later restoration, and by which emperors these repairs were made. Then follows the method of construction based on the material used. This forms the chief value and importance of Miss Van Deman's book, the result of her profound knowledge acquired through many years of study. The photographs for the plates and text cuts (in part by the author) admirably illustrate the structural details.

In Appendix A are collected the classical Latin references to Chapter I and those to Chapters II-XII. In Appendix B the remains of the aqueducts are listed. The Marcia, the first high-level aqueduct, covering 194 items; Claudia, the most magnificent, 163. Then follows an excellent and invaluable index. This work, long to be outstanding, fully maintains the high standard of the works of the Carnegie Institution. PAUL V. C. BAUR.

The Myxomycetes. A descriptive list of the known species, with special reference to those occurring in North America; by THOMAS H. MACBRIDE and G. W. MARTIN. Pp. xii, 339; 21 pls. New York, 1934 (The Macmillan Company, $6.00).—This book fills a real need by making descriptions of the slime molds available in one publication. So many new species and genera have been described since the appearance of the second edition of MacBride's "North American Slime-Moulds" in 1922, that only a specialist in a favorable location can have access to the necessary periodical literature. Fourteen pages of introduction are devoted to general morphology, including the history of the group, and collection and care of specimens, while 292 pages are given over to classification and description, with keys for the orders, families, and larger genera.

Defining the class Myxomycetes as "fungus-like organisms characterized by an assimilative phase consisting of a naked, multinucleate, mobile mass of protoplasm, the plasmodium, and a reproductive phase, consisting in most instances of a membranous spore case," the authors consider it to be the simplest class of the Fungi, equal in rank to the Phycomycetes, Ascomycetes, and Basidiomycetes. The Plasmodiophoraceæ, parasites on vascular plants, are excluded, as are the Acrasiae, the Labyrinthuleæ, and the Hydromyxales, although more information on the latter three groups is needed before they can be satisfactorily placed.

The authors recognize two sub-classes, the Exosporeæ and the Myxogastres. The former is represented by one species *Ceratiomyxa fruticulosa*, which they consider not primitive but highly specialized, while the Myxogastres include some 400 species. The Myxogastres, or endosporic Myxomycetes, are divided into four orders, instead of seven orders as proposed by E. Jahn.

There is little to criticise in the book. The reviewer was somewhat annoyed not to find the orders listed in the index. The habitat of most species is not definitely given. Possibly the majority of them are so little specialized as to make satisfactory designation of the substratum difficult, or the authors may have decided this would be of slight value since they consider the Myxomycetes to be of no direct economic importance. J. S. BOYCE.

Textbook of Histology; by ALEXANDER A. MAXIMOW and WILLIAM BLOOM. 2nd Edition. Pp. xiv, 662; 530 illus. (part in color). Philadelphia, 1934 (W. B. Saunders Co., $7.00).—The second edition of this histology text is about 150 pages shorter than the previous edition, but the length still suffices to give the beginner a comprehensive understanding of the general subject. The well-chosen bibliography at the end of each chapter compensates for any brevity. The literature cited, though not extensive, gives the student, often rather inexperienced, a source of references to supplement and verify his text and classroom studies. The subject matter is clear and concise, with points of dispute thoughtfully set apart in small print. The terminology has not been greatly altered, most definitions are fairly adequate, and few typographical errors are noted. The illustrations are clear and instructive, and the choice between diagrams, drawings, and photomicrographs (occasionally retouched) has been wisely made. The plates and figures are well labelled, and new and much clearer diagrams are substituted for those in the first edition (see fig. 81).

Since many questions discussed in histology are more relative to cytology, it seems that such details as mitochondria, Golgi apparatus, etc., needed to receive only bare mention. They have no active interest to the medical student, and their value in such a book is doubtful. More space could profitably be devoted in calling the attention of the student to the large range of variability occurring in any biological study, including histology, and that the text is only a diagrammatic and descriptive guide. He may conscientiously study some tissue in the text, and gain a rather fixed idea of the components present and of a specific arrangement; but on turning to his microscope and slides he may easily obtain a wrong impression of the tissues seen and their correlation with the text.

Although, as stated in the Preface, histological technique is not called for in a book of this type, some introductory description of stains and the affinity of various tissues for certain dyes, in outline form, would serve a worthwhile purpose. By correlated reference and slide-study the student should become more familiar with the value of stains for cytological and histological diagnosis. He should be led to realize that single slides do not give composite pictures, and that, within variable limits, certain structures are stained advantageously with quite specific dyes. R. T. HILL.

High Gods of North America; by W. SCHMIDT. Pp. 148. New York, 1933 (Oxford University Press).—Dr. Schmidt is well known as the author of "Der Ursprung der Gottesidee." He may be called an "Americanist," for his studies have included expert attention to the oldest religions of North America. Serving himself an heir to the "high god" theory of Andrew Lang, he extends it by finding High Gods *anterior* to "all other elements." Or, is this the heritage of *Genesis?* He disputes Söderblom's theory of creation through mere originators. He finds the Algonkin Great Manitu and the Selish Amotken to have been both high gods and creators. They created *ex nihilo*.

Schmidt's anthropology agrees with his theology; he holds the theory of monogenesis, discounting the possibility of *indigenous* peoples in widely scattered regions. For him the oldest Americans came with their high gods by way of the Behring Strait. Doubtless his severest task is the establishment of a tribe's ethnological age. Thereafter, he must convince us that data found by investigating the current order (in spite of linguistics without scripture) are really ancient.

Opinions vary about the character of America's oldest peoples and their ideas—nor do Orientalists agree, although their long-range studies have been longer pursued. We welcome the Americanists' researches. The present volume makes an interesting and valuable contribution to our understanding of the field. The reviewer, however, has the impression that the author is, to some extent, *illustrating*, from the American field, a preconceived theology. JOHN CLARK ARCHER.

American School of Prehistoric Research; Bulletin Number 10, May, 1934. Edited by GEORGE GRANT MACCURDY, Director.—The tenth Bulletin of the American School of Prehistoric Research contains three original articles in addition to the reports of the

Director and of the Director of the Summer School Course. The Summer School was conducted by Dr. Vladimir J. Fewkes and lasted fifty days. Nineteen archaeological collections were studied, covering the entire range of European archaeology. Especial emphasis was laid upon Central European archaeology. The greater part of the laboratory work was carried on at the State Archaeological Institute of Prague. One week was devoted to reconnaissance in the northeastern portion of Yugoslavia. Excavations were carried on at five sites in Czechoslovakia and at one site in Yugoslavia.

Miss D. A. E. Garrod, Director of the joint Palestinian expedition of the School and of the British School of Archaeology, reports in this issue upon her excavations at Wady al-Mughara during the seasons 1932-33. The exploration of the Tabūn cave revealed a stratified deposit of great depth, ranging in age from Bronze back to Acheulean. Miss Garrod's study of the various industries established the sequence of cultures in Palestine from Middle Pleistocene to recent times.

Mr. Theodore D. McCown describes the progress made in extricating from their matrices the numerous skeletal remains of fossil man found in the course of excavations in the caves of the Wady al-Mughara. This is being carried on at the Museum of the Royal College of Surgeons in London. It will not be possible to complete the work of extraction and restoration before the end of 1935. Present indications suggest that these Neanderthal Palestinians were rather nearer to modern Europeans than were the Neanderthal Europeans. The preparation and study of the specimens is being carried on under the direction of Sir Arthur Keith.

Dr. Vladimir J. Fewkes renders a preliminary report upon an archaeological reconnaissance in Yugoslavia carried on during the season of 1933 under the auspices of the Fogg Art Museum of Harvard University. Dr. Fewkes was assisted by Yugoslavian archaeologists and by Mr. Robert Ehrich of Harvard University. The reconnaissance covered the eastern part of Yugoslavia and lasted one month. During this time 122 sites were visited, nine were sounded, 38 observed from close range, and 458 recorded upon specific information gathered in the field. The trip covered ten principal geographical regions. In his report Dr. Fewkes summarizes succinctly the physiography and archaeology of each of these regions. He notes considerable cultural differentiation throughout the ages in these various regions. At present, however, the Neolithic Age alone lends itself to regional differentiation. Three regional variations are indicated: the Morava Valley system, the Lower Vardar—Upper Crna zone, and the Ključ-Krajina sector. A similar regional differentiation may be expected in the Iron Age. Dr. Fewkes' reconnaissance furnishes the necessary preliminary information for future excavations in this rich and almost unknown archaeological area. E. A. HOOTON.

Diametral changes in tree trunks; by F. W. HAASIS. Carnegie Inst. Washington, Pub. 450, 1934. Pp. 103; 4 pls., 31 figs.—This publication consists of a critical review of all the literature from 1877 to the present upon the daily and seasonal changes in diameter of tree trunks. After giving a detailed description of the chief measuring device for such studies, the dendrograph, the author takes up diurnal fluctuations, seasonal shrinkage, traumatic and prolonged shrinkage, and diametral increases, including rehydration and growth. The latter part of the publication then considers the significance of diametral changes. One hundred and thirty-eight references are cited. Fifty of these are by D. T. MacDougal.

The greatest diurnal fluctuation observed for a tree was 1.6 mm. With a continuance of dry weather the amplitude of diameter change is reduced. In rainy weather the diurnal shrinkage may be obliterated. Shrinkage in tree trunks may occur during a dry summer or autumn, during the dormant season and during the period of leaf development in the spring. When water again becomes available to the roots of trees which have exhibited a dry-season shrinkage, enlargement follows.

Increase in diameter of a tree trunk may be due to growth, or to the rehydration of previously dried tissues. The two processes may occur very close together, perhaps even simultaneously. The growth factors of greatest importance are said to be an adequate water supply and sufficient heat. Ordinarily, cell division can take place only when the cells are turgid or nearly so; the growing tissue is not usually turgid at the time the trunk is shrinking, therefore, growth is not to be expected during the daytime in clear weather. CARL G. DEUBER.

Streifzüge durch die Umwelten von Tieren und Menschen: Ein Bilderbuch unsichbaren Welten; VON J. V. UEXKÜLL und G. KRISZAT. Pp. x, 102, with 59 figs. (in part colored). Berlin, 1934 (Julius Springer, 4.80 RM.).—The environments of the snail, the worm, the fly, the bee, the toad, the bird, the dog, the child and the scientist are each pictured as perceived through such sense organs as each of these types of organisms possesses. The reader will readily appreciate how different the supposed realities of the external world can appear as soon as the perceptive mechanism is changed. The facts are reliable, even if astonishing, and the evidence is vividly illustrated. W. R. C.

Papers from the Tortugas Laboratory of the Carnegie Institution of Washington, Vol. 28; 361 pp., with 51 pls. and many text-figs. Washington (Carnegie Institution), 1934.—The importance of the investigations which have been recently conducted at this tropical marine laboratory is shown by the seventeen papers which comprise this beautifully illustrated volume. The papers deal with many aspects of marine biology, including the chemistry, physiology, reproduction, growth, regeneration, ecology and morphology of various groups of organisms from bacteria and sponges to worms, crustaceans and fishes. Because of the ability and industry of the investigators, who have worked at this laboratory, it has become one of the most renowned biological stations in the world.

W. R. C.

Studies on Some Protozoan Parasites of Fishes of Illinois; by RICHARD ROKSABRO KUDO. Pp. 44, with 8 pls. Illinois Biological Monographs, Vol. 13, No. 1, 1934.—Examination of 35 species of fish disclosed 22 species of Myxosporidian parasites, of which no less than 19 proved to be new to science. All of these are described and figured. W. R. C.

Animalium Cavernarum Catalogus; by BENNO WOLF. Parts I and II of each of 3 vols. Pp. 240. Berlin (W. Junk. Single part 18.MK., Subscription price 13.50 MK.), 1934.—This important work, when completed during the next three to four years, will list all the living species of animals hitherto discovered in all the caves throughout the world. Each cave is listed separately and a complete bibliography given. Zoologists, ecologists, paleontologists and geologists will find the work indispensable.

W. R. C.

The Palaeolithic Human Industries in the Northwest Punjab and Kashmir and their Geological Significance; by JACQUETTA HAWKES, CHRISTOPHER HAWKES and H. DE TERRA. Mem., Conn. Acad. of Arts and Sciences, 1934. Vol. VIII, 13 pp., 2 pls.—The specimens described were gathered by the Yale North India Expedition at the following sites: Chitta (Northwest Punjab), Localities I and II and Pampur and Kargil (Kashmir). At Chitta I two layers, overlying Lower Pleistocene marl, contain angular pieces of limestone. In all, 48 pieces were collected from Chitta I, of which 4 seem to be artifacts; the others must remain in the doubtful class. The four specimens may be referred to the Lower Palaeolithic and belong to a flake-industry, as opposed to a core-industry. The limestone pieces from Chitta II cannot be classed as artifacts.

At Pampur Pleistocene lake deposits form a terrace overlooking the river Jhelum. A section was taken here and revealed a layer, 3 m. below the surface, containing ash and charcoal with bones, pottery and the clay figure of an ox. Below this layer there is a deposit of loam interstratified with yellowish clay. This deposit yielded one artifact of dense green trap rock and two fragments of broken bone bearing apparent traces of cutting with some sharp-edged stone tool. The implement of trap rock may be classed as Lower or Middle Palaeolithic and is of the flake-industry type.

The authors conclude that Northern India i
hold evidence of the highest importance for oı
early man. GEORGE GRA

Applied Acoustics; by HARRY F. OLSEN and
Pp. xiv, 430; 228 Illus. Philadelphia, 1934 (P
and Co., $4.50 Fabrikoid).—Rayleigh's classical w
of Sound," published many years ago, provide
basis for most acoustical advances but in recent
been a pressing need for a book such as "Appli
interpret the theoretical principles in terms of eng
and to make available an experimental technique s
oped by the authors during their ten years' experi
research. They have been frequent contributors
particularly in connection with their developme
microphone, which has found a useful applicat
measurements. Despite the fact that it is a highly
being devoted largely to microphones, receivers a
architectural acoustics, and acoustical measureme
to a large number of readers. The publishers are
pointing out in their prospectus that it is of pa
acoustical engineers, to radio engineers, to broad
sound motion picture engineers, and to studen
matter is well presented and adequately illustr
references to papers and original sources will
Excellent instructions are given regarding experi
including different methods of accomplishing the
is a valuable contribution to the literature.

*Forty-eighth Annual Report of the Bureau of
1931.* Smithsonian Institution, Washington, D. C
Pp. v, 1220 ($2.00 in paper cover).—This large v
the report (pp. 1-21) of the Chief, MATTHEV
This gives an account of the work done by him a
in the fiscal year ending June 30, 1931. Follo
General Index (pp. 25-1220) of the Annual Re
1931; volumes 1 to 48. The work of compilin
been done by Biren Bonnerjea.

Les Lois Fundamentales et de Electricité; by L
and M. GOUDONNET. Vol. I, 2d Edition. Pp.
Paris, 1934 (Gauthier Villars et Cie. 25 francs).
this volume is that presented by M. Goudonnet t
L'Ecole pratique de Radioelectricité. The subje
similar to that which will be found in any good t
the fundamental laws of electricity.

It is interesting that the method of presenta
unusual grasp of student mentality. The auth
oughly the value of logical continuity and coher

item introduced is dependent upon the preceding one with the result that the book presents a continuous story rather than a collection of loosely related expositions.

Observatory Publications.—The following volumes have been recently received. (See earlier vol. 26, p. 88, 1933.)

OBSERVATORY OF THE UNIVERSITY OF MICHIGAN. Volume V, 1934. No. 10. A new method of driving equatorial telescopes, by R. R. MCMATH, and W. A. GREIG.—No. 11. The elements and ephemeris of comet 1933 f (Whipple); by ALLAN D. MAXWELL and HELEN M. PORTER.—No. 12. A study of Class A stellar spectra, by ROY K. MARSHALL.—No. 13. The masses and luminosities of spectroscopic binaries determined by the mass luminosity relation.—No. 14. Visual light curves of Beta Lyrae, by RALPH H. CURTISS.—No. 15. The orbit of comet 1933 f, second paper by ALLAN D. MAXWELL.—Index to Volume V.

Vol. VI, No. 1. Elements and ephemeris of Boyer asteroid 1934 EA, by ALLAN D. MAXWELL.—No. 2. Spectrographic studies of eclipsing Binaries, by DEAN B. MCLAUGHLIN.—No. 3. Atmospheric motion in Delta Cephei, by R. M. PETRIL.—No. 4. A short-lived Solar disturbance, by R. M. PETRIE and R. M. MCMATH.—No. 5. Variable velocity of the star B.D. + 56°2617(A), by CARL RUFUS.

Leander McCormick Observatory, University of Virginia. Volume V, part VII. Heights in the chromosphere from fixed and moving plates, by S. A. MITCHELL. Part VIII. Color indices and integrated magnitudes of fifteen bright globular clusters, by A. N. VYSSOTSKY and EMMA T. R. WILLIAMS.—Part IX. The photovisual magnitude of the companion of Sirius by A. N. VYSSOTSKY. The above have been reprinted from the Astrophysical Journal, lxxvii, lxxviii.

Blue Hill Observatory. Daytime radiation in 1933, with application to turbidity in American air masses, by BERNARD HAURWITZ. Cambridge (Harvard University Press, 50 cents).

Recent Advances in the Science of Meteorology and its practical Applications; by H. H. KIMBALL. Bull. Meteorological Socy. Jan. 1933.

Mt. Washington Meteorological Observatory.—The heated anemometer on Mt. Washington recorded a wind velocity of 231 miles per hour on April 12, 1934. This is regarded as correct within 10 m.p.h. Professor Charles F. Brooks, Harvard University. The previous maximum was 164 m.p.h. on April 5, 1933.

Paläohistologie der Pflanze; by ELISE HOFMANN. Pp. vii, 308; 153 figs. Vienna, 1934 (Julius Springer, 24 RM., bound 25.20 RM.).—The first complete account of the histology of fossil plants has been prepared by Dr. Elise Hofmann and is now offered by Julius Springer of Vienna. This piece of work is unquestionably fine and will be of the utmost value and interest not only to students and investigators in the field of fossil botany but to those interested in the study of living plants as well. The preliminary chapters of the work contain first of all an account of the development of paleobotanical investigation which is, in itself, an excellent brief history of this field of botanical science. This is followed by an account of the state of preservation of fossil plant remains, methods of preparation for study and suggestions relating to the determination of tissues. In the main part of the work, Dr. Hofmann presents all the facts concerning the histology and anatomy of fossil plants within each of the plant groups. By this method the reader is able to obtain quickly a complete account of the anatomy and tissue structure, so far as they are known, for the members of any particular group. The text is abundantly supplied with excellent figures many of which are reproductions of original photographs. An extensive bibliography concludes the volume. H. CASTLE.

Fog; by ALEXANDER MCADIE. Pp. 23; 53 pls.; 30 by 23 cm. New York, 1934 (The Macmillan Company, price $2.50).—This volume, by the Director Emeritus of the Blue Hill Meteorological Observatory of Harvard College, is uniform in scope and format with "Clouds" by the same author, published by the Harvard Press in 1930. The plates are instructive and are, in general, well done. They are not confined to depicting fog, some of them showing high clouds, lightning flashes, snowflakes, and the like. Plate XXIV is a beautiful picture of a water-spout. In the short introductory text the author comments hopefully upon the possibility of the artificial dissipation of fog, but a really practical scheme for doing this in the near future seems to the reviewer to be highly improbable. FRANK SCHLESINGER,

Yale University Observatory.

OBITUARIES.

DR. FRANK CARNEY, the geologist, professor at Denison University of geology and geography 1915-1917, and at Baylor University from 1929, died on December 13 at the age of sixty-six.

DR. COLLIER COBB, professor of geology at the University of North Carolina, died on November 28 at the age of seventy-two.

DR. HORACE LAMB, the prominent English mathematician, professor of mathematics at the University of Adelaide, also later at Owens College and the University of Manchester, died on December 4 at the age of eighty-five.

DR. WILLEM DE SITTER, professor of astronomy at the University of Leiden, died on November 21 at the age of sixty-two.

PUBLICATIONS RECENTLY RECEIVED.

Lexique Technique Anglais-Francais; par Guy Malgorn. 2d edition. Paris, 1934 (Gauthier-Villars, 25 fr.).

The Universe Around Us; by Sir James Jeans. Third edition, revised and enlarged. New York, 1934 (The Macmillan Co., $4.00).

The New Background of Science; by Sir James Jeans. Revised edition (Macmillan Co., $2.50).

The Spirit of Chemistry. An introduction to Chemistry for Students of the Liberal Arts. Alexander Findlay. New York, 1934 (Longmans, Green & Co., $4.00).

Ions, Electrons, and Ionizing Radiations; by James A. Crowther. Sixth Edition. New York, 1934 (Longmans, Green & Co., $4.25).

General Astronomy; H. Spencer Jones. New York, 1934 (Longmans, Green & Co., $3.75).

The Changing World of the Ice Age; Reginald A. Daly. New Haven, 1934 (Yale University Press, $5.00).

Geologie Appliquée; E. Raguin. Paris, 1934 (Masson et Cie, 120 Boulevard Saint Germain, 38 fr.)

Carnegie Institution of Washington. News Service Bulletin. The Ruins of Quirigua.

The Navy-Princeton Gravity Expedition to the West Indies in 1932. U. S. Hydrographic Office, Washington: 1933.

Kleiner Grundriss der Theoretischen Physik; Arthur Haas. Berlin, 1934 (Walter de Gruyter & Co., RM. 5.30).

The Carbohydrates; by E. F. Armstrong & K. F. Armstrong. Monographs on Biochemistry. New York, 1934 (Longmans, Green & Co., $6.50).

Molecole E/Cristalli; Enrico Fermi. Bologna, 1934 (Nicola Zanichelli Editore).

Getting Acquainted with Minerals; by George L. English. Rochester, New York, 1934 (Mineralogical Publishing Co.).

TTA UNI
Acc. No........
LIBRARY

AMERICAN JOURNAL OF SCIENCE

FEBRUARY 1935

IS THE "ROOTS-OF-MOUNTAINS" CONCEPT DEAD?

CHESTER R. LONGWELL.

Late in the year 1854 Archdeacon J. H. Pratt, seeking to explain the discrepancy between geodetic and astronomic measurements in India, raised a further problem by demonstrating that the observed lateral attraction exerted by the Himalayan mass and associated highlands is only a small fraction of the computed value, assuming uniform density in the crust.[1] Early in the following year G. B. Airy, Astronomer Royal, suggested an explanation that has since become famous as the "Airy hypothesis."[2] This concept pictures a light shell of variable thickness resting on rock of higher density. According to this view, segments of the Earth's crust behave, in a general way, like icebergs immersed in water, the thicker parts reaching to greater depth as well as to greater height than thinner segments. Large mountain units supposedly are buoyed up by downward protuberances or "roots"; for this reason the concept is known as the "roots-of-mountains" hypothesis.

Airy's discussion, comprised in four printed pages, gives only a general outline of the concept, without consideration of important implications. He speaks of the dense subcrustal rock as *lava*, and for the sake of clarity in presentation he supposes this material below the outer shell to be "perfectly fluid." In reality he had no such primitive view, for he states, "This fluidity may be very imperfect; it may be mere viscidity; it may even be little more than that degree of yielding which (as is well known to miners) shows itself by changes in the floors of subterraneous chambers at a great depth . . . ."[3] Elsewhere he says, "It is quite as possible that the immersion of the lower projection in the lava may be too great, as that the elevation may be too great . . . ,"[4] thus suggesting the possibility of departures from perfect equilibrium. The ways in which balance is disturbed and the exact mechanism by which it is restored are subjects not mentioned in Airy's paper. Furthermore, Airy makes no suggestion as to the possible depth to which "roots" extend. His final sentence, however, warns against the application of his concept to minor topographic features. "It applies only to the computation of the attractions of high tracts of very great horizontal extent, such as those to the north of India."

---

[1] Pratt, J. H.: On the attraction of the Himalaya mountains, and of the elevated regions beyond them, upon the plumb-line in India. Phil. Trans. Roy. Soc., 145, pp. 53-100, 1855.

[2] Airy, G. B.: On the computation of the effect of the attraction of mountain-masses, as disturbing the apparent astronomical latitude of stations in geodetic surveys. Phil. Trans. Roy. Soc., 145, pp. 101-104, 1855.

[3] Op. cit., p. 101.

[4] Op. cit., p. 104.

Pratt continued to study the general problem, and a few years later he put forward the hypothesis, now familiar in geophysics and geology, that topographic variations are compensated by differences in density which disappear at a nearly uniform depth below sea level.[5] This conception was adopted by Hayford and Bowie in their well-known studies of deflection residuals and gravity anomalies. On the other hand W. Heiskanen, the Finnish geodesist, has done extensive work in computing gravity values on the basis of the Airy hypothesis of a light outer shell with variable thickness. Many geologists also have favored this conception as more consistent with geologic facts and inferences than the Pratt hypothesis.

In recent papers Bowie has urged two arguments against the Airy conception. The first of his objections is based on the values of gravity anomalies in mountain regions.[6] Such anomalies, Bowie states, should be strongly negative if mountains have deep roots, because the center of gravity in a column reaching to the level of compensation would lie abnormally deep and the gravitative attraction would be correspondingly weak. Since the Hayford anomalies in mountain regions do not have consistently negative values increasing with heights of the stations, Bowie concludes that the "roots" idea is improbable. His second argument attacks the conception of "roots" as inconsistent with physical laws.[7] To form a "root" the granitic rocks of the outer shell must be forced downward, presumably by plastic flow, to displace the heavy rocks of the substratum. Granting that this could be accomplished, the "tip of the root" would be subject to such enormous stress differences that it would tend to spread out and disappear.

---

[5] Pratt, J. H.: On the deflection of the plumb line in India caused by the attraction of the Himalaya Mountains, and of the elevated regions beyond; and its modification by the compensating effect of a deficiency of matter below the mountain mass. Phil. Trans. Roy. Soc., 149, pp. 745-778, 1859.

[6] Bowie, W.: A gravimetric test of the "roots of mountains" theory. U. S. Coast and Geodetic Survey, Serial No. 291, 1924.

[7] Bowie, W.: Notes on the Airy or "roots of mountains" theory. Science, 63, pp. 371-374, 1926.

Bucher recently indorsed these two arguments of Bowie, and pronounced the Airy view inadequate.[8] Bucher also cites the experiments by Greig, Shepherd, and Merwin, which demonstrate that granites weaken and melt at lower temperatures than basalts. "This result," says Bucher, "destroys the physical basis for Airy's concept of 'roots of mountains' and with it all theories based upon it."[9] The present writer is dissatisfied with this summary verdict, and asks a suspension of judgment until the evidence is reviewed.

Several modern versions of the Airy hypothesis are conceivable. An extreme view might be that every individual range of considerable size is supported by a long narrow column of granitic rock that tapers downward, in vertical section resembling the root of a tooth. Another possible version is represented in Fig. 1. The Rocky Mountains and associated high-

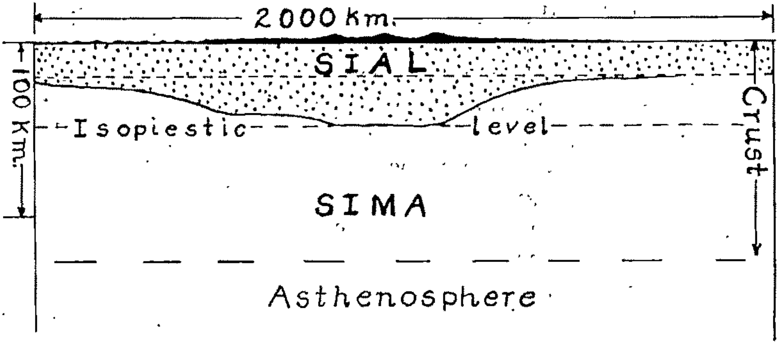


Fig. 1. Diagrammatic representation of a segment of the Earth's crust, in an east-west section through the Rocky Mountains and the Colorado Plateau. Curvature of the surface not shown. The part of the section above sea level is represented in solid black; the remainder of the outer light shell (acidic rock or sial) is stippled, with a line of short dashes indicating a normal depth of 20 km.; the basic rock (sima) below the sial shell is shown in white. Vertical exaggeration nearly five times. The base of the crust, at an unknown depth, is suggested by the line of long dashes.

Three distinct surfaces relating to the crust, as here represented, are likely to be confused in discussions of isostasy.

(1) Compensation for topography is conceived to be complete at the base of the sial, a highly irregular surface.

(2) Above the *isopiestic level*, which passes through the deepest part of the sial shell, large blocks of equal cross-section are equal in mass. If the sial and sima in each of these blocks could be thoroughly mixed, compensation would then be according to the Pratt concept, and the depth of compensation would be uniform at the isopiestic level.

(3) Adjustment by horizontal transfer presumably takes place below the base of the crust, which is the deepest of the three surfaces.

---

[8] Bucher, W. H.: Pp. 41-42 in "The deformation of the earth's crust." Princeton University Press, 1933.

[9] Op. cit., p. 302.

lands form a broad topographic unit, in which much of the local relief is the result of differential erosion. Conceivably the acidic shell is thickened under the entire unit, with much less irregularity at the base than at the top. Such a concep assumes compensation distributed to considerable distances horizontally, instead of strictly local compensation. Possibly the under side of the thickened segment reflects in a broad way the major topographic divisions of the mountain zone, bu there are no narrow columns with sharp "tips" reaching downward. If the figure were drawn without vertical exaggeration the thickened segment would not exhibit an abrupt downward bulge; there would be no sharp angles in any part of the contact between sial and sima.

Perhaps Airy conceived of adjustment by slow lateral flow in the upper part of the basic subcrust, even where the outer shell is thinnest. Such a view does not accord with modern geophysical thought. Possibly the level at which strength is normally at a maximum lies in the sima below all or most of the sial, and the asthenosphere lies much deeper in the zone of basic rock. Formation of the broad "root" in a mountain zone may take place as follows: A geosyncline, filled with a thick prism of sediments, begins to fail under horizontal stresses, with folding and thrust-faulting in the outer zone crushing and plastic flow at depth. There is a tendency to force the excess material upward, causing uplift of the deformed zone; but gravity sets a limit to this action, and the mechanism of isostatic adjustment comes into play. The upper part of the sima yields, perhaps in part by bending and shearing, in part by plastic flow. At greater depth adjustment is accommodated by lateral transfer in the asthenosphere.

This suggested interplay of orogenic and gravitative forces is admittedly speculative and qualitative. Any inquiry into the *modus operandi* of crustal deformation leads to the field of speculation, beyond the realm of quantitative geology. We see the effects of orogenic stresses in a superficial zone, and can only guess the thickness of the shell involved and the mode of deformation at depths beyond observation. Barrell, in his helpful studies relating to isostasy, pictured a strong crust of moderate thickness resting on a zone of weakness, the asthenosphere.[10] Granted this arrangement, presumably the entire thickness of the crust is involved in orogenic disturbance, with strong deformation localized in weak belts. Failure under compression tends to thicken the entire crust along these belts. Relief by bulging upward is limited by gravitative control, and can involve only the uppermost portion of the light shell. In the lower part of the crust the sima is forced down into the asthenosphere and distributed laterally. The lower part of the sial shell takes part in the slow downward movement, and thickens progressively at the expense of the lower basic portion of the crust.

---

[10] Barrell, J.: The strength of the Earth's crust. Jour. Geol., Vol. 22, Nos. 1-8, 1914; Vol. 23, Nos. 1, 5, and 6, 1915.

Schemes similar to that outlined above have been proposed by numerous students of tectonics. During the years following his studies on the strength of the crust, Barrell, in his graduate teaching, vigorously pressed the view that the entire thickness of the crust is involved in orogenic deformation, and that adjustment to overloading in orogenic zones is accomplished by movements in the asthenosphere. Bucher has put forward essentially the same mechanism,[11] and he cites the work of Meinesz, who has advanced similar views, although Meinesz defines the crust as the sial shell. Others have suggested, with variations in detail, the thickening of the light shell in orogenic zones, but the present paper can not attempt to cite the literature fully. The definition of the crust and the general scheme of deformation outlined by Bucher are accepted here as a working hypothesis, but with the suggestion that thickening of the outer light shell in orogenic zones is a logical consequence. Bucher does not admit any considerable thickening of the shell, because of the three objections stated earlier in this paper. These objections will now be discussed critically.

Bowie's argument that "roots" should be reflected in large negative anomalies appears to be directed against the extreme view of local compensation by narrow, nearly isolated prongs of sial reaching to great depth. There is no suggestion in Airy's paper, however, that he himself held such a conception; and the present paper makes no defence of this special view. Bowie's argument loses much of its force when it is applied to the conception represented in Fig. 1. The thickened sial under the Rocky Mountain region or under the broad Andean Highlands would have the general form of a thin plate with large horizontal extent. Such extensive plates have very small differential effects on gravity values, as Bowie and other geodosists have explained.[12] Therefore pronounced effects of the thickened shell, in the form of strong negative anomalies would not be expected. It may be urged, fairly enough, tha some effect should be evident, inasmuch as the thickness o the plate is an appreciable fraction of its horizontal extent There is good suggestion that such an effect has been detected by geodetic work. Bowie found that the best depth of compensation, taking account of all stations in the United States is 60 kilometers; whereas the best depth for mountain stations considered alone is 95 kilometers.[13] If these figures are accepted, they suggest that compensation under low plains extends to a depth much less than 60 kilometers, and that mountain masses are supported by veritable "roots." It is true tha Bowie discounts the testimony of stations outside mountainous areas.[14] Other geophysicists, however, attach considerable importance to Bowie's results, quoted above, and admit them as evidence supporting the Airy hypothesis.

---

[11] Op. cit., pp. 210 fol.

[12] Bowie, W.: See, for example, Fig. 12, p. 72, and p. 102, in *Isostasy*, (E. P. Dutton & Co., 1927.)

Bowie's second argument has already been answered indirectly. If no narrow, sharp-tipped columns of sial are assumed to reach deeply into the sima, then the difficulties in forming and maintaining such features, discussed by Bowie are avoided. Thickening of the sial plate in orogenic zones may result logically from a combination of horizontal and vertical forces, as explained above. Any possible tendency, on the part of such forces, to produce deep, narrow roots is perhaps defeated by the factors suggested by Bowie; as a result the base of the thickened sial has only broad, rounded protuberances that reflect in a general way the larger surface irregularities, but show no abrupt relief as compared with the eroded highlands. At temperatures well below the melting point, i does not appear that "roots" of this nature would be unstable

We come now to Bucher's statement that the Airy hypothesis is rendered null and void by recent determinations at the Geophysical Laboratory. Greig, Shepherd, and Merwin, after careful experiments, made the startling announcement that the melting temperatures for granites are considerably lower than those for basalts.[15] Geologists and geophysicists at once recognized in this result a death blow to several prominent concepts, including Joly's hypothesis of thermal cycles, which assumes as a fundamental postulate that granite will remain solid in molten basalt. As the Airy hypothesis does not involve directly the relative melting temperatures of any rocks whatever, the reason for summary rejection of the hypothesis is not clear. Bucher gives no argument with his statement, and therefore a brief analysis is in order.

---

[13] Op. cit., p. 96.

[14] Op. cit., p. 102.

[15] Greig, J. W., Merwin, H. E., and Shepherd, E. S.: Melting granite and basalt in the laboratory. Bull. Geol. Soc. Am., 40, 94-95, 1929.

In his original outline of the hypothesis Airy spoke of "lava" beneath the outer light shell; but he did so merely to simplify the explanation of fundamental principles in his concept. Nowhere in his paper does he state that the rock forming the light shell must be inherently stronger than the denser rock directly beneath, although the reader may feel that such a view is tacitly implied. Certainly some of Airy's disciples have regarded such a conception as either essential or convenient, and more than one has explained that the *strong* sial is forced down into the *yielding* sima. This view is admirably suited to the mechanisms invented by Wegener and Joly, and the attractive writings of these two have no doubt served to implant in current thought rather special versions of the Airy concept. Attention is again invited to Fig. 1 of this paper as representing another version that conforms to all essentials of the original hypothesis, and at the same time takes account of later developments in geophysics and geology.

Although the figure is diagrammatic and qualitative, it does not ignore current views as to the probable thickness of the sial shell. Jeffreys estimates that the granitic layer in parts of Europe is only 10 km. thick.[16] However, he recognizes also a deeper shell of "intermediate" composition, with a thickness of about 20 km.[17] Some other geophysicists admit only a single superficial shell, with a thickness of 20 km. or more. Fig. 1 represents under non-mountaineous country an acidic shell with uniform composition, 20 km. in average thickness. To simplify the discussion, this layer is supposed to make sharp contact with heavier basic rock beneath. Near the contact both layers normally have temperatures well below fusion, and there is no wide difference in strength. Consider a broad highland belt that has an average height of 3 km. above the adjacent plains. Taking the density of the outer shell as 10 per cent less than that of the lower layer, and assuming that the highlands are supported by a "root," the sial must be

---

[16] Jeffreys, H.: The Earth. See pp. 105-106. Cambridge University Press, 1929.

In a recent paper by L. Don Leet, it is shown that the basis for recognizing a "granitic" or other outer shell is open to serious question. (Velocity of elastic waves in granite and norite; *Physics*, 4, No. 10, 375-385, 1933.)

[17] Op. cit., p. 151.

thickened downward an average of 27 km., and the total thickness of the shell in the mountain zone is 50 km. (about 31 miles). These figures are illustrative only, but they suggest the order of thickening to be expected, under the Airy hypothesis, beneath the Rocky Mountains. Under Fermor's inference that eclogite (density 3.4) underlies the light shell in mountain zones,[18] a thickening of 12 km. would be sufficient to support a highland mass 3 km. high, and the total thickness of sial in the Rocky Mountain segment would be only 35 km. (22 mi.).

Under conditions represented in the figure, pressures in the crust would be uniform on a horizontal surface through the lowest part of the "root"; this is the isopiestic level of Washington. However, the rock is conceived to be generally strong at this level, and if anything should occur to disturb isostatic balance, adjustment presumably would take place, after the strength of the crust is exceeded, by vertical movements in the crust, with horizontal transfer at a much deeper level, where strength is assumed to be nearly or altogether absent. This is the general mechanism indorsed by Bucher and by Bowie, but it is here applied to a crust compensated by the Airy method.

No steps in forming or maintaining the sial "root," as discussed on pages 84-85, are affected by the *relative* melting temperatures of granite and basalt. It may be asked, however, whether the *actual* melting temperature of granite does not have an important bearing on the hypothesis. Is this melting temperature, as recently determined, so low that fusion certainly would occur at the base of the shell a few tens of kilometers thick? If so, the Airy concept in any form encounters a serious difficulty.

So far as the writer is aware, there is at present no basis for drawing with confidence curves representing temperatures and melting points deep in the crust. Various commendable attempts have been made, but the results must be considered tentative because of important unknown factors. Measured temperature gradients vary widely, and therefore attempts to extrapolate beyond the shallow zone of observation encounter a double difficulty: uncertainty as to the proper starting values, and ignorance of possible changes in the gradient with depth. L. H. Adams, Jeffreys, and others have contributed temperature-distribution curves based on the supposed thermal history of the Earth starting with solidification from an original molten state. The curve by Jeffreys indicates a temperature above 1000° C. at 100 km. depth.[19] Jeffreys emphasizes the uncertainties involved in the calculations. However, geophysicists are pretty well agreed that the depth at which granitic rocks must eventually undergo fusion is much less than 100 km., because of the low melting temperature of such rocks and their high content of radioactive elements. Holmes, even before the recent determinations of melting temperatures, stated that a granitic layer 55 km. thick would be permanently fused towards the base.[20] His argument, however, was directed against the assumption that the sial layer is normally as thick as 55 km., and not against the possibility of local and temporary thickening.

---

[18] Fermor, L. L.: The relation of isostasy, earthquakes and vulcanicity to the earth's infraplutonic shell. Geol. Mag. (6), 1, pp. 66-67, 1914.

It is conceivable that granitic batholiths, which commonly rise in mountain zones at a late stage of the orogeny, result partly from heat developed by orogenic movements and partly from forcing of granitic rocks to abnormal depths as the sial shell is thickened. Considerable fusion would not necessarily cause prompt destruction of the "root." There appears to be a tendency for batholiths to rise vertically, or nearly so, into the higher parts of folded zones. Heat would be dissipated by convection and conduction, and the thickened shell might recover from partial melting without appreciable loss in thickness. Destruction of a "root" could be accomplished only by lateral shift of the fused sial, which probably would be opposed by enormous frictional resistance. Perhaps slow lateral migration of the weakened sial does occur, resulting in widening of the "root" and uplift of extensive plateaus adjacent to a mountain belt. Such spreading of the sial might account eventually for considerable lowering of the mountain surface, and thus would help meet the objection that excessive erosion is required for permanent removal of mountains under the isostatic theory.[21] Jeffreys saw this difficulty and suggested the solution mentioned above.[22]

The discussion so far has been designed to meet specific arguments that have been directed recently against the Airy hypothesis. No defense of the hypothesis, however, should fail to mention the significant results of Heiskanen, who was the first to test the Airy concept in more than a qualitative way. Recalculating gravity anomalies for all stations in the United States on the assumption of compensation concentrated in a light outer shell, he obtained a mean value lower than that announced earlier by Bowie, who had assumed uniform distribution of compensation to a constant depth. The results of Heiskanen's calculations for stations in Europe are equally satisfactory.

---

[19] Op. cit., p. 154.

[20] Holmes, A.: Some problems of physical geology and the Earth's thermal history. Geol. Mag., 64, p. 265, 1927.

[21] Chamberlin, R. T.: Isostasy from the geological point of view. Jour. Geol., 39, pp. 9-10. 1931.

[22] Op. cit., p. 295.

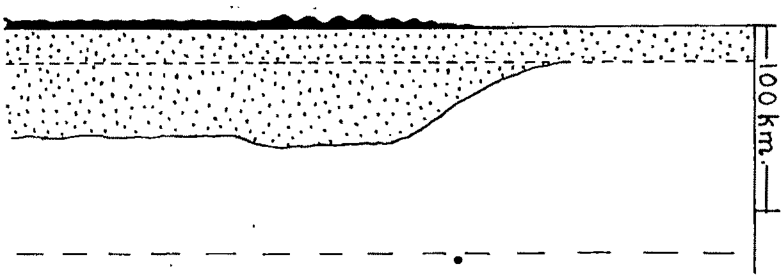
In answer to the question in the title of the present paper, therefore, it seems possible to continue use of the Airy concept in speculative geology. If the discussion should end with this statement, the writer would of course be branded as an unqualified disciple of Airy and hence an opponent of Pratt's view. For some reason that is not clear, most students who discuss these two hypotheses of compensation speak of them as mutually exclusive, and in no degree reconcilable. In view of the large and distinguished following which each of the concepts has enjoyed, it is conceivable that both contain elements of truth, and that the two may be combined to form a useful eclectic hypothesis.

Although much can be said in favor of the Airy concept, its universal application to explain major topographic features would strain credulity. The high plateau of southern Africa is not associated with any youthful mountain belts, and it is difficult to imagine a mechanism by which the shell of normal sial could have been thickened sufficiently to elevate this tableland. Moreover, the degree of thickening that must be assumed to support the Himalayan-Tibetan highland appears somewhat excessive, in view of the physical-chemical properties of granite. On the other hand the Pratt conception of compensation by variable density, while it seems artificial and improbable in its extreme form, has also much to commend it. Continents appear to stand above ocean floors by virtue of fundamental differences in crustal density. Within the continents, Washington found that in a general way the densities of igneous rocks vary inversely with altitudes,[23] though the variation is not known to be quantitatively sufficient for compensation. The exposed continental rocks are dominantly granitic, but the composition is extremely heterogeneous in detail. It is possible that physical and chemical changes at some depth in the crust cause increases and decreases of density in large masses of rock, with consequent raising and lowering of surface areas.

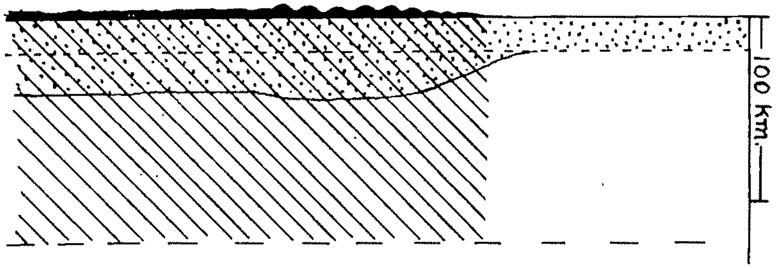
---

[23] Washington, H. S.: Isostasy and rock density. Bull. Geol. Soc. Am., 33, pp. 375-410. 1922.

As an illustration of the possible combination of the two hypotheses, suppose that the crustal density in the Himalayan



A. Compensation entirely according to the Airy concept of a light shell variable in thickness.



B. One-half of the compensation by deficient density in the crust below the highlands, according to the Pratt concept; one-half of the compensation by thickening of the sial shell. Deficient density, indicated by diagonal lining, assumed in both divisions of the crust. Other conventions as in Fig. 1.

Fig. 2. Part of the Himalayan-Tibetan highland, with two suggestions of compensation. Vertical exaggeration about five times.

block is low enough to account for 30 per cent of the average altitude—about 5 km.—above the adjacent plain. This deficiency in density, in relation to adjacent segments of the crust, may be in the sial shell, in the lower basic part of the crust, or distributed through both of these zones. The "root" of sial sufficient to buoy up the remaining 70 per cent of the mountain mass would have an average depth of about 31.5 km. instead of 45 km., and the total thickness of sial beneath this highest mountain unit would be about 57 km. (35 mi.). If the defect in density is sufficient to support one-half of the mountain mass the assumed downward thickening of the sial is only 22.5 km. (Fig. 2). There is nothing inherently improbable in such a union of the principles outlined by Airy and Pratt. The larger problems of tectonics are too complex to be solved by any simple formula, and it is unfortunate to discard any concept that may help the solution.

YALE UNIVERSITY,
NEW HAVEN,
CONN.

HYPOTHYRIDINA VENUSTULA (HALL) IN PENNSYLVANIA.[1]

BRADFORD WILLARD.

ABSTRACT.

An unquestioned outcrop of Tully has for the first time been recognized in central Pennsylvania. *Hypothyridina venustula* (Hall) is present. This is the first known occurrence of this important guide fossil in the State and is its southernmost, recognized extension in the Appalachians.

INTRODUCTION.

The wide distribution of *Hypothyridina* and the importance attached thereto in stratigraphic paleontology, make any additional data on its occurrence of interest. The recognition of the characteristic Tully species *Hypothyridina venustula* (Hall) for the first time in Pennsylvania is, therefore significant. With its identification, beds of Tully age with Tully fossils are unequivocally recognized in an exposure in the State. The literature dealing with the Devonian of Pennsylvania contains many references to occurrences of the Tully, most of them misidentifications. Up to the present the only report of anything assignable to the formation has been that of an occurrence recognized by Butts.[2] He has found a thin limestone in south-central Pennsylvania carrying *Chonetes aurora* at the correct stratigraphic position for the Tully. The writer recently announced the discovery of Tully in central Pennsylvania many miles east of Butts's localities.[3] This outcrop is in a road cut along the south bank of the Susquehanna River one-half mile above South Daville in Northumberland County. A faunule of Hamilton species with elements suggestive of the Laurens member of the Tully of eastern New York[4] was found in a ten-foot limestone lying between the Genesee and Hamilton shales. The limestone varies from hard, compact, gray rock to sheared, shaly limestone. For it the author has proposed the name Rush member of the Tully.

---

[1] Published with the permission of the State Geologist of Pennsylvania.

[2] Butts, C.: Geologic section of Blair and Huntingdon counties, central Pennsylvania. This Journal, 4th ser., vol. **46**, pp. 523-537, 1918. Also oral communication.

[3] Willard, Bradford: A Tully limestone outcrop in Pennsylvania. Penna. Acad. Sci., pr. vol. **8**, pp. 57-62, 1934.

[4] Cooper, G. A.: Stratigraphy of the Hamilton group of eastern New York, part II. This Journal, 5th ser., vol. **27**, pp. 6-7, 1934.

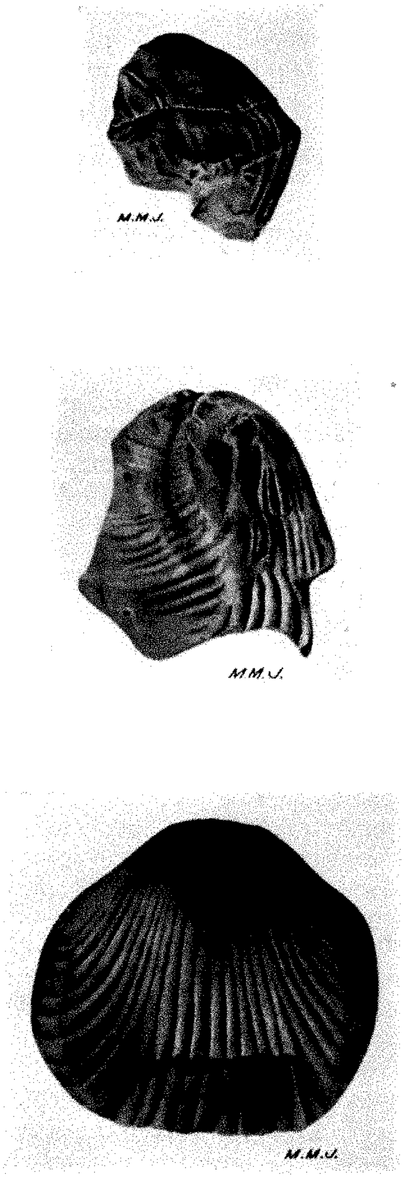


Fig. 1. *Hypothyridina venustula* (Hall) from Pennsylvania compared with typical New York material. a. Smaller of the two fragmentary specimens from South Danville. b. Larger of the two fragmentary specimens from South Danville. c. Example from eastern New York. (x 2.)

No other outcrop has been found although Tully is reported from many well logs in northern Pennsylvania.[5]

FOSSILS OF THE TULLY OF PENNSYLVANIA.

The faunule of the Rush member of the Tully limestone at South Danville is as follows:

Lopholasma cf. carinatum Simpson
Pleurodictyum ?
Corals, indet.

Crinoidea, columnals

Bryozoa, undet.

Lingula sp.
Stropheodonta ?
Lepostrophia interstrialis (Vanuxem)
Schuchertella variabilis (?) Prosser
Atrypa spinosa Hall
Hypothyridina venustula (Hall)
Cyrtina hamiltonensis Hall

Spirifer mucronatus var. posterus (?) Hall and Clarke
Elytha fimbriata (Conrad)
Ambocoelia umbonata (Conrad)
Brachiopod, unnamed*

Styliolina fissurella (Hall)
Tentaculites bellulus (?) Hall

Orthoceras sp.
Bactrites aciculatus (Hall)

Phacops rana (Green)
Dalmanites boothi (Green)

* This is a Martinia-like brachiopod known also from the Laurens member of the Tully in eastern New York.

This faunule is at once allocated to the Tully by the presence of *Hypothyridina venustula.* As this occurrence is unique for Pennsylvania, a brief description of the specimens with figures is in order.

Two specimens of *Hypothyridina* were found in the upper part of the Rush limestone where the exposed beds had weathered to a buff, shaly appearance. Both examples are fragmentary. The smaller of these (Figure 1a) is an irregular fragment of the internal cast of an external mold about 1 cm. long by an equal width. It is from the right, anterior portion of the lateral area of a brachial valve. Eight rounded costae are discernible. The region of deflection between the gently sloping upper portion of the lateral surface adjacent to the median fold and the more remote, vertical portion of that surface is preserved. None of the original shell substance remains, nor is there any indication of the internal characters. This specimen would probably have remained unidentified were it not for the coexistence of a second, much better preserved individual.

---

[5] Fettke, C. R.: Subsurface Devonian and Silurian sections across northern Pennsylvania and southern New York. Bull. Geol. Soc. Am., vol. **44**, pp. 601-660, 1933. Note: These data can now be supplemented by additional, later well records on file with the Pennsylvania Topographic and Geologic Survey.

The second specimen (Figure 1b) is also part of a brachial valve and is about two-thirds complete. It, too, is an interior cast of an exterior mold. The shell had been laterally distorted by crushing. A low, median fold is present becoming more prominent anteriorly. It appears to have been marked by 12 rounded costae, although not all are distinctly preserved. The right, lateral surface, represented nearly intact, is marked by between 23 and 25 costae which have been partly lost through exfoliation. Rounded in the anterior region, these grow flatter near the hinge line. Along the anterior margin of the valve in the region of the fold, a row of pit-like depressions is observed. This is probably the most distinctive feature of the specimen and is an unmistakable character, proving identity. The posterior region immediately anterior to the beak had been partly exfoliated before the natural mold formed so that the cast shows the faint outline of the characteristic, oval muscle scar but no ovarian sinuses are visible. While there is no question of identity, there is a point of comparison which should be observed for these specimens.

Cooper (oral communication) has noted variations in *Hypothyridina venustula* in eastern New York. Typically, the species has fewer costae on the fold than the second South Danville specimen shows (compare Figure 1b with 1c), but individuals with fully as many median costae as the Pennsylvania example are known from the Laurens member of the Tully in Otsego County, New York. The similarity of the Pennsylvania specimen to the Laurens multicostate variety is at once apparent. The Pennsylvania examples were taken to the United States National Museum and there compared with material collected by Dr. Cooper in eastern New York. By this means the identity of the South Danville specimens is absolutely determined.

CONCLUSION.

The presence of strata of Tully age is established unequivocally in central Pennsylvania through the discovery, in an otherwise predominantly Hamilton faunule, of *Hypothyridina venustula*. The specimens are most closely related to a multicostate, eastern New York variety of this species. The Pennsylvania specimens not only establish the presence of rocks of Tully age and extend the Tully fauna into a region where it has not been hitherto recognized, but they register the southernmost occurrence of *Hypothyridina* in the Appalachians although the organism has been reported farther south in the Mississippi Valley.[6]

During the 1934 field season the author has found additional evidence for the presence of Tully limestone in south-central Pennsylvania.

HARRISBURG,
PENNSYLVANIA.

---

[6] Savage, T. E.: The Devonian rocks of Kentucky. Kentucky Geol. Surv., ser. VI, vol. 33. Tully fauna discussed pp. 17-18, 1930.
————: Tully fauna at the base of the black shale in east-central Kentucky. Bull. Geol. Soc. Am., vol. **40**. No. 1, pp. 112 and 249, 1929.

BASAL RELATIONS OF THE GALENA DOLOMITE IN THE UPPER MISSISSIPPI VALLEY LEAD AND ZINC DISTRICT.

G. MARSHALL KAY AND GORDON I. ATWATER.

INTRODUCTION.

The Upper Mississippi Valley Lead and Zinc District lies to the east of Dubuque, Iowa, in Iowa, Illinois and Wisconsin.[1] In extending studies of the formations from outcrops farther to the northwest into this district, it has been found that the base of the Ordovician Galena formation, which, as the Prosser limestone is conformable on the top of the Decorah formation in northeastern Iowa, comes to lie disconformably on the underlying beds. It is the purpose in this paper to discuss the relations that are believed to pertain between the Galena and the underlying formations, and to point out certain relations within the formations in the district that have not been previously recognized, but may have a bearing on interpretations of ore genesis.

For a half century prior to Bain's applying the name Platteville to the limestones succeeding the St. Peter sandstone,[2] they had been called "Trenton." "In all these localities, the entire thickness of these lower limestones, which can clearly be identified with the Trenton and associated limestones of the east, is less than fifty feet. The deposit above is a grey, or drab-colored limestone, and very friable, and is called by Dr. Owen the 'upper magnesian limestone'; we have designated it in the classification of the rocks as the 'Galena limestone.' "[3]

Bain defined the Platteville as extending to the top of the green shale bed that is now known to be the southeastern extension of the lowest member of the Decorah formation, the Spechts Ferry shale. The succeeding beds have been placed consistently in the base of the Galena as the "oil rock member," the Guttenberg member of the Decorah, and the thickness assigned has varied from 2 to 16 feet.[4] Though geologists have placed a disconformity at the top of the limestones of the "glass-rock" member of the Platteville, this hiatus is of small magnitude where present at all; whereas the "oil-rock member" or Guttenberg, which succeeds the Spechts Ferry, is in some localities overlain by younger Decorah limestones of the Ion member, and elsewhere by Galena dolomite. Thus, there is a marked disconformity above the "oil-rock," and only a minor one at the top of the limestones of the Platteville.

---

[1] Bibliography in Emmons, W. H.: The Origin of the Deposits of Sulphide Ores of the Mississippi Valley, Econ. Geol. 2, 256, 1929.

[2] Bain, H. F.: Zinc and Lead Deposits of Northwestern Illinois, U. S. Geol. Survey, Bull. 246, 18, 1905.

[3] Hall, James, in Foster, J. W. and Whitney, J. D.: Geol. Lake Superior Land District, Part II, "The Iron Region," U. S. 32d Congr., Spec. Session, 3, Exec. Doc. 4, 146, 1851.

STRATIGRAPHY.

Stratigraphic sections have been measured at many localities in Grant County, Wisconsin, Dubuque County, Iowa, and Jo Daviess County, Illinois. The study has not been extended into the many mines within the district. Laboratory examinations of the sediments were made by Mr. Atwater in the sedimentation laboratories at Columbia University and the State University of Iowa. Those having direct bearing on the interpretations are included in this paper. The writers are indebted to Professors R. J. Colony and P. F. Kerr for their counsel on petrographic and mineralogic aspects of the problem.

Character of analytical studies. The sedimentary analyses included separation and examination of insoluble residues, determination of the dolomite content and study of thin sections. The small amount of residue from the limestones and dolomites, large proportion of clay grades, and difficulty in disaggregation of these fine grades, and the rather large proportion of secondary minerals in some of the samples made the size-grade distributions meaningless or misleading. The graphs presenting the total quantity of insoluble residue in the samples are in some cases of significance in interpreting the stratigraphic relations.

Distinctive forms of secondary silica that would aid in stratigraphic correlations were not obtained.[5] The grades of residues smaller than 1/32 mm. were examined with a petrographic microscope to determine whether this material represented primary clastic grains or secondary quartz and other authigenic minerals. Authigenic feldspars were present in the samples;[6] associated with them were authigenic quartz crystals. These minerals were not diagnostic in correlation or identification of horizons, but were of importance in interpreting the petrographic history of the rocks. An effort was made to separate the heavy minerals of the residues; the small quantity and size precluded there being significant results.

---

[4] Grant, U. S.: Lead and Zinc Deposits of Wisconsin, Wisconsin Geol. and Nat. Hist. Survey, Bull. 14, 40, 1906;

Cox, G. H.: Lead and Zinc Deposits of Northwestern Illinois, Illinois Geol. Survey, Bull. 21, 26, 1914;

Trowbridge, A. C., and Shaw, E. W.: Galena and Elizabeth Quadrangles, Illinois Geol. Survey, Bull. 26, 45, 1916, etc., 1916.

[5] McQueen, H. S.: Insoluble Residues as a Guide in Stratigraphic Studies, Missouri Bureau of Geology and Mines, 56th Biennial Report, Appendix 1, 1-32, 1931.

The percentage of $CaMg(CO_3)_2$ in samples was obtained by applying Lemberg's solution to ground fragments between ¼ and ⅛ mm. in diameter and counting the grains under a binocular microscope.[7] Polished sections were also stained with this solution, and the study of these sections served to substantiate mineral identifications made in thin sections, and in learning the textural relations of the calcite and dolomite.

The thin section study of the samples was found to be a more important aid in interpretation. This study gave the petrology of the rocks, explained some seeming anomalies in certain dolomite analyses, and emphasized the advantages in the thin section examination of carbonate sediments to augment other types of analysis.

Sections Northwest of the Lead and Zinc District.

The full sequence of Decorah and Galena beds is represented in the vicinity of Guttenberg, Iowa, a few miles northwest of the district; see Fig. 1. The Platteville limestone is succeeded by the Decorah formation with three members, the Spechts Ferry, Guttenberg and Ion in ascending order. The regional stratigraphy and correlation of the members has been described.[8]

The Spechts Ferry member, about eight feet thick, is composed of blue-green, argillaceous, laminated clay shales with intercalated, thin lenticular limestones that are most abundant in the lower part. A thin metabentonite persists about a foot from the base.[9] The topmost bed of the member is an unusually persistent and distinctive 4 to 8-inch bluish, medium-textured limestone containing black phosphatic and pyritic nodules and minute fossils. Because both this top bed and the meta-bentonite bed near the base persist where the member is thin in sections near Platteville, Wisconsin, it has been believed that the thinning of the member is due to convergence rather than to disconformity; however, the bed may properly belong in the base of the Guttenberg.

---

[6] Tester, A. C., and Atwater, G. I.: Occurrence of Authigenic Feldspars in Sediments, Jour. Sed. Petrol., 4, 23-31, 1934.

[7] Briard, V. E.: Study of Staining Methods Applied to Well Cuttings, M.S. Thesis (unpublished) State University of Iowa Library, 1932.

[8] Kay, G. Marshall: Stratigraphy of the Decorah Formation, Jour. Geol., 37, 339-371, 1929; Mohawkian Ostracoda: Species common to Trenton faunules from the Hull and Decorah formations, Jour. Paleont., 8, 328-344, 1934.

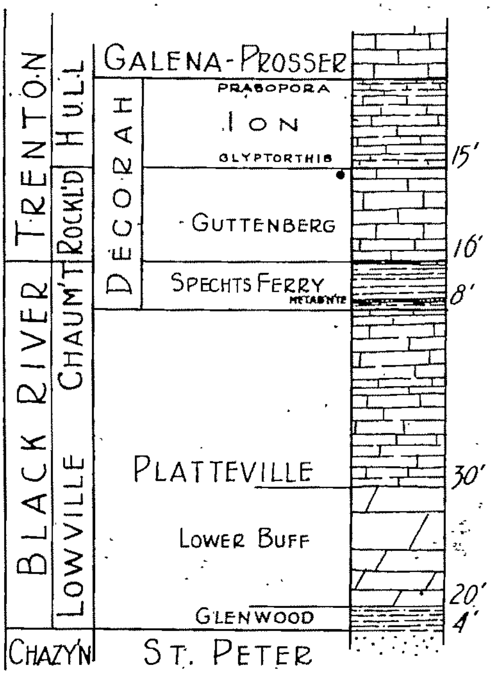


FIG. 1. Columnar section of the Decorah and adjacent formations in the vicinity of Guttenberg, Clayton County, Iowa.

The Guttenberg member is composed of fine-textured, gray, tan-weathering, fossiliferous limestone becoming darker and coarser textured toward the top. Partings of the brown, bituminous "oil-rock" shale occur in the member, which has a thickness of about 16 feet at Guttenberg. It is slightly thinner to the north, and a little thicker as the "oil-rock member" of earlier geologists in certain sections in the lead and zinc district. The Ion member is composed for the most part of blue-gray, rather fine-textured, somewhat argillaceous, thin-bedded limestone that is limited above and below by zones of greenish, argillaceous, calcareous shale having intercalated limestone beds. The lower zone is characterized by the presence of the brachiopod *Glyptorthis bellarugosa* (Hall); the upper zone farther north contains an abundance of specimens of a species of the bryozoan *Prasopora*. The member is about 15 feet thick. It is succeeded by the four to eight-inch beds of light gray, fine-textured Prosser limestone, the lower formation of the Galena group in Minnesota.

---

[9] Kay, G. Marshall: Stratigraphy of the Ordovician Hounsfield Metabentonite, Jour. Geol., 39, 370, 1931.

Sections in the Lead and Zinc District.

In the mineral district, the Platteville limestone is succeeded by a thin Spechts Ferry member of the Decorah formation that

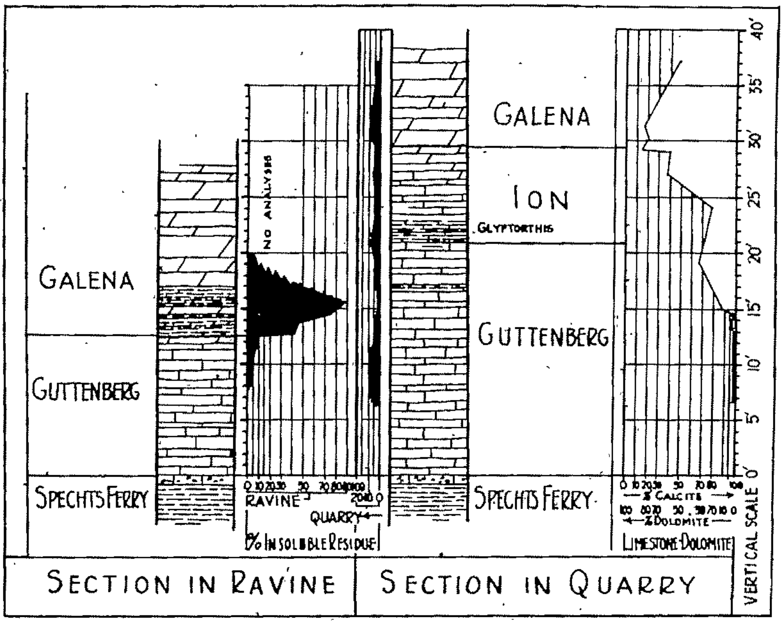


FIG. 2. Tabular summary of two sections at Spechts Ferry, Iowa. That in the road-ravine is one-eighth mile west of that in the quarry back of the station. The columnar sections of both are accompanied by graphs representing the percentages of insoluble residues in significant beds; and the upward change from limestone to dolomite in the quarry section is shown in the calcite-dolomite analysis graph.

retains the Hounsfield metabentonite near its base, and the phosphatic nodule bed at the top. In sections at Spechts Ferry, Iowa, Potosi, Wisconsin, and elsewhere, this member is similar in character and thickness to its more northern sections in northeastern Iowa. In other sections farther east, as at Platteville, it is thinner, but the lower and upper beds seem the same as in the thicker sections. The next succeeding beds differ from section to section. The character of the variation is particularly apparent in localities where there are two well exposed sections near to each other. Such localities are those at Spechts Ferry, Iowa, and Beetown, Wisconsin.

Sections at Spechts Ferry, Iowa. Two sections an eighth mile apart are exposed at Spechts Ferry, in the northwest quarter of section 4, T. 90 N., R. 2. E. (Peru Township, Dubuque County), Iowa. The lithology of the lower beds has been presented elsewhere.[10] It will be sufficient to present details concerning the sequence above the Spechts Ferry shale; the sections are described in Tables I and II and in Fig. 2.

TABLE I.

Section of beds above the Spechts Ferry member of the Decorah formation in the quarry southeast of Spechts Ferry Station,

Dubuque County, Iowa.

	Thickness of bed	Top of bed to top of Spechts Ferry member
GALENA DOLOMITE:		
Buff, coarse-textured, somewhat friable dolomite containing vein calcite.		
DECORAH formation:		
Ion member:		
Gray, fine-textured, one to two inch beds of limestone becoming browner, coarser textured and containing crystalline calcite toward the top	6′	29′ 4″
Greenish-gray, argillaceous, calcareous shaly limestone with purplish, coarse-textured, fossiliferous limestone interbeds — Glyptorthis zonule	2′ 6″	23′ 4″
Guttenberg member:		
Gray, fine-textured, thin-bedded limestone with some shale partings and "oil-rock" in the lower part	20′ 10″	20′ 10″
Spechts Ferry member, 8′ 6″ thick.		

---

[10] Kay, G. Marshall: Stratigraphy of the Decorah Formation, op. cit., 646.

TABLE II.

Section of beds above the Spechts Ferr
along the roadside southwest of Sp

GALENA formation:
Gray and brown, coarse-textured, friat
dolomite.
Gray-blue and tan shale with thin beds
brownish dolomite near base: ....
Brownish, medium-textured dolomite in o
ledge ....
Yellowish clay shale ....
Interbedded brownish and grayish dolomi
and grayish shales ....

DECORAH formation:
Guttenberg member:
Undulating two and three inch beds
brownish-weathering, fine-textured, limesto
with a few intercalated beds of "oil-rocl
shale; darker and coarser textured near to
Spechts Ferry member, 8′ 6″ thick, the top
two beds: the lower, 6″ thick, of homogeneo
grayish, fine-textured limestone containi
pyritic and phosphatic nodules; the upper,
4″ bed forming a falls in the stream.

In the quarry sequence, there is a
Decorah beds for the region through
the base of the Ion. The succeeding
dolomitic (see right hand graph, Fig. 2
supported by their containing partially
the gradual change to dolomite, and i
the beds is similar to that of the typica
and not similar to the more massive G
mite curve is more readily interpreted
sections. These reveal that the upper 3
stone has been so metasomatized as to be
original calcite coquina texture has beer
replaced by dolomite that has crystalli
with abundant scattered euhedral dolo
3A. The contact of the Ion and Galen
cated by the abrupt steepening of the
seeming anomaly of a higher dolomite
Ion than in the Galena in the thin sec
that there has been introduction in the G
of late vein calcite that is later than th
upper Ion. It crystallized in large a
inch or more in diameter, and replace
texture of the rock; see Fig. 3C and 3
this late stage calcite are present in the

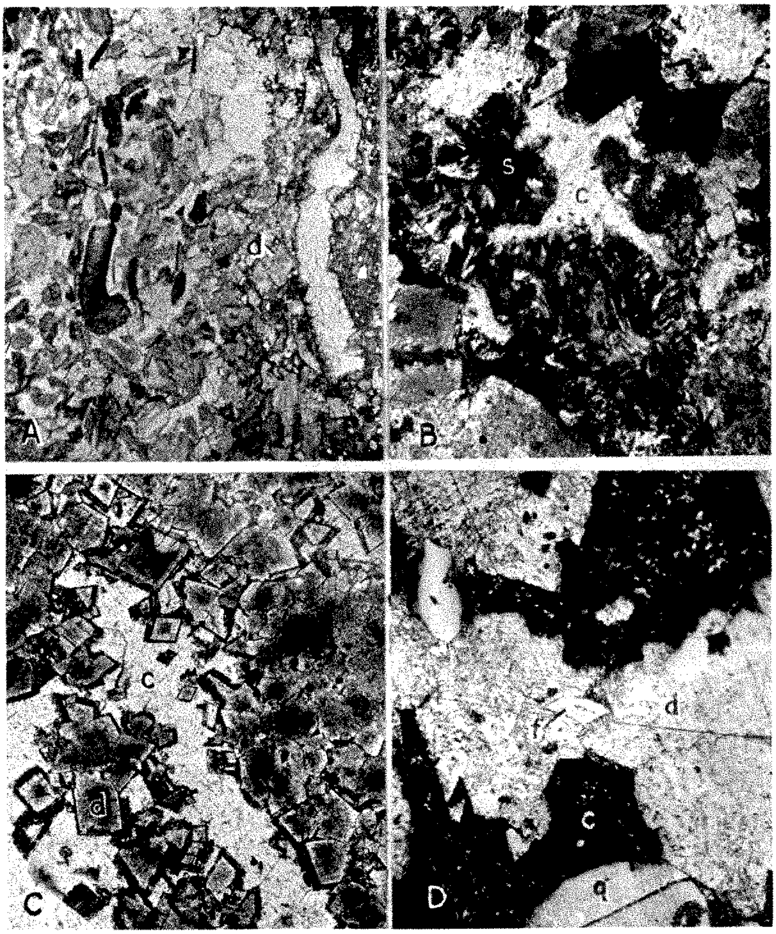


Fig. 3. Rock sections illustrating the petrology of the limestones and dolomites; Spechts Ferry quarry section.

A. Upper Guttenberg limestone, a coquina with interstitial calcite; a few dolomite rhombs (d) replacing some of the original rock; thin-section, plain light, × 35.

B. Lower Ion limestone having silicified fossils of chalcedony (s) being replaced by later calcite (c); thin-section, crossed nicols, × 50.

C. Basal Galena dolomite, calcite (c) having invaded and somewhat replaced dolomite (d), rhombs of which have ferruginous margins; thin-section, plain light, × 30.

D. Basal Galena dolomite, same rock as in C; clastic quartz fragment (q) at bottom; probably an authigenic feldspar (f) in middle; polished surface stained with Lemberg's solution, × 100.

The ravine section is similar to that in the quarry through twelve and a half feet of the Guttenberg. The succeeding beds contrast markedly, and the disconformable relationship of the Galena to underlying beds is apparent from a comparison of two sections. The insoluble residue content in the quarry section is low and rather uniform throughout. In the lower part of the ravine section, the residue content is consistently below 10%, and the differences between the curves in the two localities for this part of the section are not significant, there being somewhat more silicification of beds in the ravine section. The beds above the twelve and a half feet of Guttenberg in the ravine section are high in insoluble residue, the chief constituents of which are in the silt and clay grades; the curve shows a marked departure from that for the corresponding elevations in the quarry section.

The distance between the ravine and the quarry is less than an eighth mile. The known consistence of Guttenberg lithology in the region precludes possible original differences of this quantity in clastic content; in fact, such clastic beds are unknown in the member. It might be thought that the high residue beds in the ravine section comprise the accumulated residues of a considerable thickness of leached limestones, such as do form shaly beds at other localities (see p. 107). But in the Spechts Ferry ravine there are interbeds of thin dolomite, and it is not probable that leaching would have been of such selective nature as to remove the carbonate from most of the beds while leaving intercalated beds quite unaffected. The beds seem of normal, evenly laminated bluish-gray shale, and the absence of slumping that might accompany leaching and the field appearance seem to eliminate the possibility that the beds are residues. Above these beds occur typical thick-bedded, buff, sugary-textured, somewhat cherty Galena dolomites, with insoluble residues similar to those in the uppermost beds in the quarry sequence.

The basal Galena beds in the ravine section seem to be clastic beds deposited upon the eroded surface of the Guttenberg. That there has been erosion of the Ion and upper Guttenberg to allow these clastic shales to rest on middle Guttenberg limestone is demonstrated by the fact that the Glyptorthis zonule persists in the quarry section and in all sections extending across this interval in the region. The lowest Ion zone probably was uniformly extensive over the area at the time of its deposition, and later has been removed locally. The differences in the two sections are not a result of the limestones of the Ion member, having been dolomitized to a greater depth in the ravine section than in that in the quarry as has been suggested.[11]

Beetown, Wisconsin, sections. Another pair of sections in close proximity are those southeast of Beetown, in Sec. 30, T. 4 N., R. 4 W. (Beetown Township, Grant County), Wisconsin. Along State Road 14, a short distance south of the village, the Glyptorthis zonule of the Ion is exposed in a small quarry east of the road. The succeeding section is described in Table III:

TABLE III.

Section along State Road 14, just south of Beetown, Wisconsin.

	Thickness of bed	Top of bed to base of Ion
DECORAH formation:		
Ion member:		
Yellowish green, calcareous shale—apparently the Prasopora zonule; covered by slope wash, exposed	1′	16′ 0″
Purplish gray and mottled tan and gray two to twelve inch beds of medium-textured limestone passing down into somewhat argillaceous limestone with intercalated greenish shale and purplish crystalline limestone......	10′	15′ 0″
Greenish, calcareous shale with intercalated one to four inch beds of purplish and mottled limestone; some beds quite fossiliferous, Glyptorthis zonule near base	5′	5′
Guttenberg member:		
Gray, fine-textured limestone.		

In the ravine 50 yards to the southwest across the road there are heavy ledges of brownish, coarse-textured dolomite that lie above thin bedded, shaly dolomitic beds 12 feet above the top of the Guttenberg; the dissimilarity in the lithology of the beds between 15 and 16 feet in each of the sections is evident in Fig. 4.

Section ten miles west of Platteville in Sec. 23, Harrison Township, Grant County, Wisconsin. In some cases leaching has been important in producing shaly beds at the base of the Galena dolomite. In Sec. 23, T. 3 N., R. 2 W., Wisconsin, a concentration of "oil-rock" partings in the Guttenberg limestone has produced an "oil-rock" shale. The exposure is just below the bridge south of the center of Sec. 23; see Table IV.

---

[11] Kay, G. Marshall: Op. cit., 645.

TABLE IV.

Section in Sec. 23, Harrison Township, Grant County, Wisconsin.

	Thickness of bed
GALENA formation:	
Buff, friable dolomite beds mostly concealed.	
Greenish-gray clay with lenses of yellowish clay and silt very irregularly distributed	6″
Ocher-yellow clay silt with thin lenses of gray clay and poorly defined three-inch bed of dolomitic rock near base	1′ 2″
Purplish and ocher-yellow clay and silt interbedded. 57% insoluble residue	5″
DECORAH formation:	
Guttenberg member:	
Ocher-yellow silty clay with lenses and laminae of clay	8″
Chocolate-red, bituminous shale with "oil rock" characters containing some irregularly laminated yellowish beds; silicified fossils common	11″
Spechts Ferry member:	
Yellowish clay with many black, irregular phosphatic nodules, particularly at base; lacks bedding	8″
Greenish, argillaceous shale with fossils on bedding planes.	

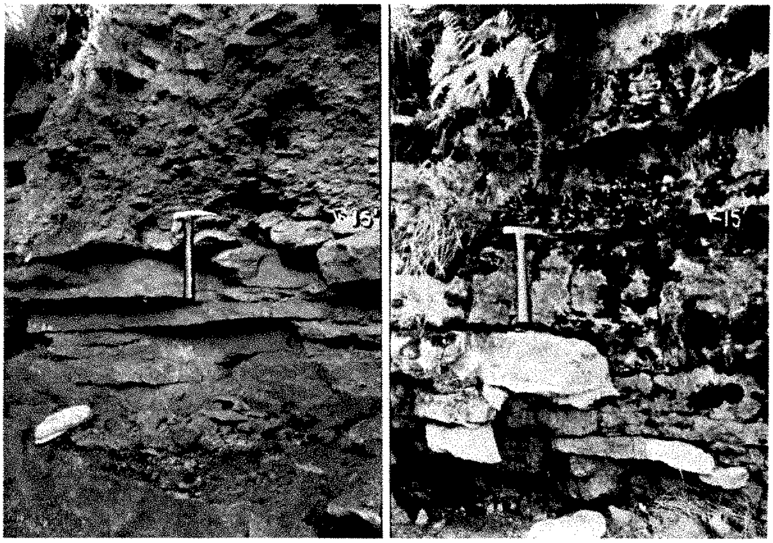


Fig. 4. Illustrations of the lithology of the beds at fifteen feet in the sections south of Beetown. The left illustration is along the roadside, that on the right in the ravine; the hammer head is at fifteen feet from the top of the Guttenberg limestone in each picture.

The lowest beds in this section are typical Spechts Ferry shale. The succeeding bed is the residue of the top bed in the normal Spechts Ferry section, a limestone containing many phosphatic pellets. The "oil-rock" shale has the characters of the partings in typical Guttenberg limestone, and the normal fossils; in fact, a gradation from this bed to unleached Guttenberg limestone can be observed to the west of the exposure. The succeeding bed is low in residue (7.4%); the purplish and ocher clay above it contains 57% of insoluble residue, and is presumably the base of the Galena.

Upstream to the west there is normal Guttenberg limestone that becomes more magnesian and grades up into beds that are not distinguishable from Galena dolomite.

Other sections in the district. It has been stated that the recorded thickness of the beds above the Spechts Ferry shale is variable in the region. There are 17 feet of Guttenberg and about four feet of Ion, including the Glyptorthis zonule, across the river from Spechts Ferry in a ravine west of Potosi. In the section two miles west of Platteville, heavy beds of dolomite overlie about twelve feet of Guttenberg. At the Sinsiniwa River bridge on U. S. Highway 20 west of Galena, Illinois, the most of the Ion is preserved. These sections further illustrate the range of beds beneath the Galena dolomite.

Magnitude of the Disconformity.

Though there is disconformity at the base of the Galena formation in the Lead and Zinc district, the Galena-Prosser limestone lies with essential conformity on the Prasopora zonule at the top of the Decorah formation in northern Iowa and southern Minnesota. The lower Receptaculites zone, fifty to sixty feet from the base of the Prosser, continues southward into the dolomite and occurs from thirty to fifty feet from the base in the Dubuque region. It would seem that the disconformity is one representing a time during which some twenty feet of Prosser beds were deposited farther north. The disconformity seems to be limited to the region southeast of Guttenberg, Iowa, and Patch Grove, Wisconsin. Whether it represents a horizon exactly at the base of the Prosser or a little higher has not been determined.

SUMMARY AND APPLICATIONS.

In the Upper Mississippi Valley Lead and Zinc District, there is a distinct disconformity at base of the Galena dolomite, bringing that formation in contact with beds of the Ion and of the Guttenberg ("Oil-rock member") members of the

Decorah formation. This is in contrast to the stratigraphic relations in sections northwest of the district, where the Prosser limestone of the Galena group lies conformably on the Ion; this conformity continues into Minnesota. It is believed that the outcrop in northeastern Iowa and Minnesota was more peripheral to the dome Wisconsinia in middle Ordovician time than the lead and zinc district, and that deposition continued in the former region while erosion took place locally in early Prosser time in the latter.

There is conformity between the Platteville limestone and overlying Spechts Ferry ("blue-green") shale from Minnesota into the lead and zinc district. If there be disconformity beneath the Spechts Ferry within the district, it would seem to be of much smaller magnitude than that at the base of the Galena dolomite.

The "oil-rock" has been given an important place in the interpretations of the ore genesis in the lead and zinc district. It has been believed that the Galena is particularly likely to be ore-bearing where it is underlain by a considerable thickness of "oil-rock" shale. The "oil-rock" shale has been said to be thickest in basins that have been interpreted as being depositional in their origin. It is probable that at least a part of the "oil-rock" shale is the result of the leaching of the limestones with shale partings of the Guttenberg member of the Decorah formation. This has been shown to be the case in certain sections where the pre-Galena disconformity succeeds the Guttenberg. Such leaching should have resulted in a concentration of a considerable thickness of limestone into a thin "oil-rock" shale, and thus the top of the shale residue should occur at relatively lower elevation than the unleached limestone. This interpretation may account for some of the "oil-rock," and has not been applied to a detailed structural study of the beds in the mineral region.

There are in the district three sorts of shales that may occur in quite similar stratigraphic positions. First, there are the calcareous shales deposited widely and persistently as the Glyptorthis zone at the base of the Ion member; these beds are relatively more argillaceous as one goes northwestward from the district. Stratigraphically, they should occur fifteen to twenty feet above the top of the Spechts Ferry ("blue-green") shale, and have Guttenberg limestone intervening. Second, there are clastic shales, high in insoluble residue, deposited as basal sediments of the Galena dolomite upon the pre-Galena disconformity. These seem most prevalent where the Galena lies low on the underlying sequence; they are absent in many sections, and varied in character and thickness. Third, there are the "oil-rock" shales, reddish shales that are at least in some cases the leached residue of the Guttenberg limestones with their shaly partings, the "oil-rock member" of earlier geologists. These shales immediately succeed the top of the Spechts Ferry shale, and have been consistently so described. Whether all of the "oil-rock" shales are of this sort has not been ascertained; there may be a fourth type of shale—an originally deposited "oil-rock" shale.

The Galena dolomite is essentially the equivalent of the Prosser limestone of southern Minnesota, as can be demonstrated through the study of the intervening sections. Within the lead and zinc district, beds equivalent to the lowest Prosser are lacking and are represented in the pre-Galena disconformity. Thus there is evidence that dolomites in the district are equivalent to limestones farther northwest. It has been shown that some dolomites within the district have resulted from the metasomatism of limestones. It is not known, however, that the Galena dolomite is of this sort; it may be that calcium-magnesium carbonates were deposited in the district synchronously with calcium carbonates in Minnesota. From the fact that limestone beds are intercalated within the dolomites in northeastern Iowa, and in some instances rather pure limestones are immediately adjacent to pure dolomites, it is inferred that if the two lithologies were not primary deposits, there were primary differences in lithology that resulted in a selective alteration of some limestone beds to dolomites.

The purpose of this paper has been to present the understanding of the stratigraphic relations of beds that have been considered relevant to interpretations of ore genesis in the lead and zinc district. The effect of these new interpretations on the understanding of the mineral deposition has not been considered.

Columbia University,
New York City.

FLAWS AND TEAR FAULTS.

ELWYN L. PERRY.

INTRODUCTION.

In the course of recent work with Princeton University field parties in the Beartooth Mountains near Red Lodge,[1] Montana, several "faults" associated with the Beartooth overthrust in the eastern part of the range were studied by the writer. These dislocations, of which two are particularly notable, were found to have large horizontal components of displacement along essentially vertical planes and to be genetically related to the accompanying overthrust.

The diagram below (Fig. 1) shows the general relationships of the chief transverse dislocations. The sedimentary (Paleozoic) strata involved in the overthrust structure outcrop in a belt along the mountain front and, since they are nearly vertical in attitude, they show very well the pronounced drag near the transverse structures and indicate clearly the nature of the movement along each. As far as could be determined, the strata (Fort Union) below and in front of the thrust sheet are unaffected by the transverse faults, i.e. the fractures are limited to the overthrust sheet. The largest "fault" (the Mount Maurice) shows a relative lateral displacement of about 10,000 feet, while other fractures of the same system show displacements as small as a foot or less. A more detailed description of the structure of this area will appear under separate title.

Examination of the literature describing the above type of dislocation reveals considerable confusion in nomenclature and as a result a more comprehensive survey of the terminology and a review of the history of study of this general type of structure has been attempted below, in order to summarize the existing information.[2] It has seemed inadvisable to mention more than a few representative examples of the structures discussed, although they have been described from several parts of the world.

---

[1] Thom, W. T., Jr.: Science, 72, pp. 117-118, Aug. 1, 1930.

[2] The writer is particularly indebted to Dr. W. H. Bucher, of the University of Cincinnati, for advice and encouragement in the preparation of this paper.

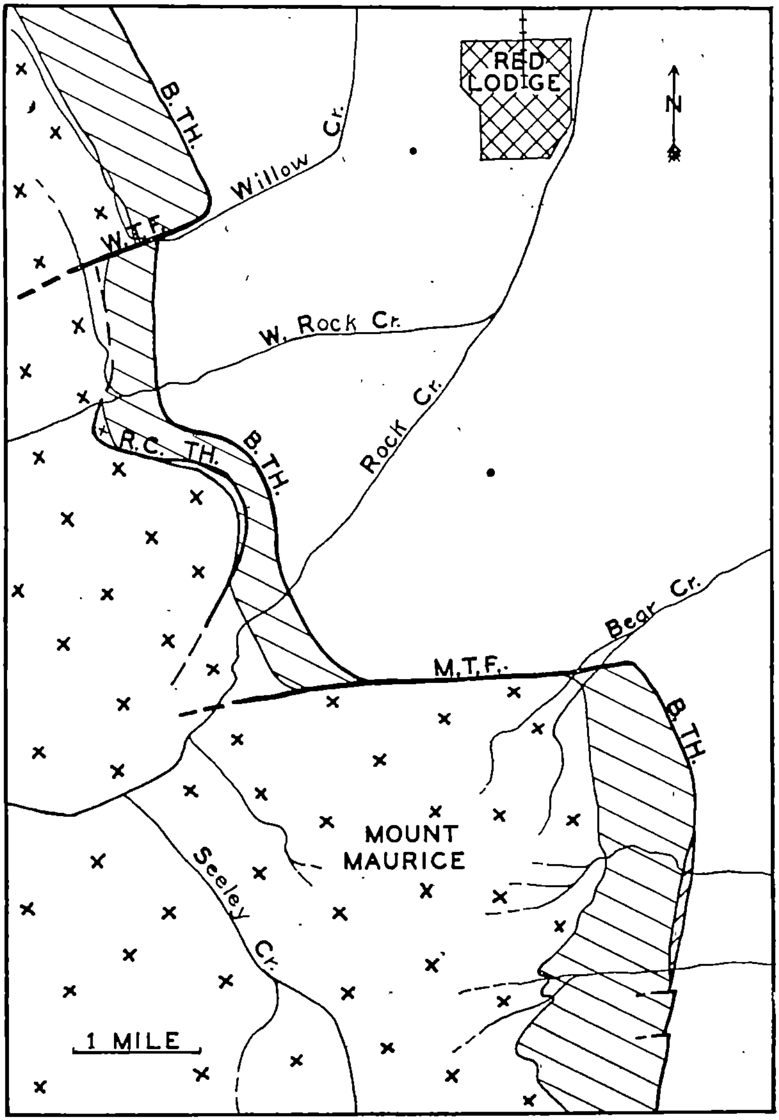


Fig. 1. Tectonic Map of Beartooth Front at Red Lodge, Montana. Key: Crosses, Pre-Cambrian and Tertiary igneous rocks; Lined areas, Paleozoic strata; Blank area, Fort Union sandstones, coal, etc. B.TH., Beartooth Overthrust; R.C.TH., Rock Creek (secondary) Overthrust; M. T. F., Mt. Maurice Tear Fault; W. T. F., Willow Creek Tear Fault.

CLASSIFICATION.

There are at least three varieties in the general class of dislocations which show a relatively important horizontal displacement of the mass on one side with respect to the one opposite. The three varieties differ in origin and structural detail, although they are otherwise similar in some degree.

The first variety is illustrated by the example described above, in which a vertical plane of dislocation, transverse to the regional structure, is caused by local adjustment within a thrust sheet. The amount of relative movement involved may amount to several thousand feet. Most writers consider such fractures to be restricted to the thrust sheet, but some consider them to penetrate the passive block as well. These transverse dislocations are known to many as "tear faults," although other terms have been applied, as will be discussed below.

A second variety of fault showing horizontal displacement is that described from several mining districts, particularly in the western United States, where in areas of complex faulting associated with igneous intrusions some of the local adjustment took place horizontally along approximately vertical planes. These displacements are described as comparatively limited in extent and associated with "complex normal faulting." A genetic connection with igneous intrusions is either stated or implied in many cases.

The third variety is that represented by the great San Andreas fault along which horizontal movement was observed in 1906. This, unlike most faults with horizontal displacement, is in the main a longitudinal rather than a transverse structure. It seems probable from the observed relation of the San Andreas fault to the associated structures that the forces involved in the formation of this and a few similar faults, differ in several ways from the forces responsible for the first two varieties mentioned, but the determination of the place of this fault in any classification awaits more exact information on the early geologic history of the structure,[3] particularly with the object of demonstrating whether the recent horizontal "shearing" is also characteristic of earlier movements. Chamberlin,[4] Clark[5] and others have implied that such faults in the Coast Range province were originally normal faults and once developed they have served as convenient planes along which any subsequent stresses would be relieved, although the latter might in themselves be incapable of initiating such structures.

---

[3] Reed, R. D.: Geology of California, Tulsa, Okla., pp. 11-12 and 31-44, 1933.

[4] Chamberlin, T. C.: Econ. Geol., 2, p. 591, 1907.

[5] Clark, B. L.: Bull. G. S. A., 41, pp. 794 and 818-819, 1930.

A possible fourth variety, genetically associated with folding (without distinct overthrusting ?) is suggested by some descriptions, such as one by Ashley[6] of faults in the coal measures of Pennsylvania, but such a possibility must necessarily be checked by future observations with this point in mind. Many descriptions of faults showing horizontal displacement contain insufficient information to indicate how they should be classified (genetically), for example, Jonas and Stose[7] have described vertical "transverse faults" in the Lancaster District of Pennsylvania, on which the movement "appears to be largely horizontal," but this region is structurally so complex that their exact genetic relationship remains in doubt. It is evident that the classification suggested above may be expanded or modified in the future as more accurate information of the required sort is available.

The three principal types of dislocations enumerated above are all in some degree recognized by Ransome[8] in his well-known paper concerning horizontal dislocations on faults and are mentioned in part by other writers in the discussion which followed,[9] but neither in these papers nor elsewhere, to the writer's knowledge, has an attempt been made to differentiate clearly between these geometrically similar dislocations of diferent origin. Failure to make such distinction, on at least a theoretical basis, is responsible for part of the confusion of terminology. In some respects the three or more types are genetically similar, in that they are produced by horizontal thrusting stresses which are unequally distributed. This unequal distribution may be obtained in two ways, 1) through variation in the strength (and direction) of thrusting stresses in adjacent parts of the translated mass, or 2) through local variation in resistance set up in opposition to the forward movement of the thrust mass. An analysis of the two pos-

---

[6] Ashley, G. H.: Penn. G. S., Bull. M6, 4th Ser., Part I, p. 73, 1928.

[7] Jonas, A. I., and Stose, G. W.: Lancaster Quad., Atlas of Penn. No. 168, pp. 61-63, 1930.

[8] Ransome, F. L.: Econ. Geol., 1, pp. 777-787, 1906.

[9] Econ. Geol., 2, Discussion by Spurr, Fairchild, Willis, Chamberlin, Reid, and others, 1907.

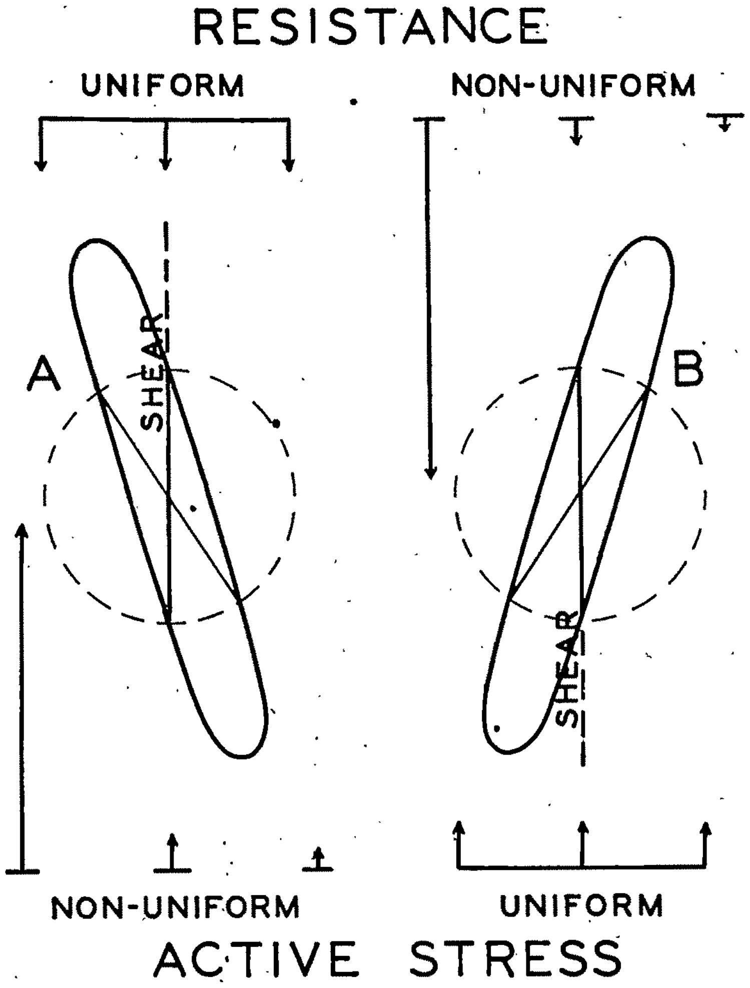


Fig. 2. An application of the strain ellipse to an analysis of the forces causing vertical dislocations along which there is dominant horizontal displacement. The diagram indicates the resolution of stresses and strains in a horizontal plane. A. Rotation and shear caused by unequal distribution of thrusting stress. B. Rotation and shear caused by non-uniform resistance to the movement of the translated mass.

sible cases in terms of the strain ellipse is indicated in Fig. 2. In each case rotational stresses are set up in a horizontal plane (or planes) oriented approximately parallel with the original thrusting stress. The three types differ, on the other hand, in the cause and relationships of the initial stress—the only basis of a significant classification. It is obvious that the varieties of the general class of structures discussed cannot be determined in all cases, hence a term is needed for the general class as well as terms for the more important varieties.

GENERAL TERMS.

Only one of the varieties of dislocations showing horizontal displacement has received recognition by the application of specific terms. The comment which follows is hence first concerned with a general survey of the terms which have been applied to the whole class. These several terms refer, in other words, to a *genus* of dislocations of which the tear fault is one *species* while the other species remain as yet unnamed.

Eduard Suess,[10] in 1885, was among the first to direct attention to the general structural type by describing European examples in some detail and introducing the term "Blatt." This supplanted the more general term, "Ueberspründe," which had been previously applied to some extent. *Blatt*, as Suess points out, was a term taken from the mining parlance of the time and given a technical (geological) meaning: to the miners this term apparently had a simple descriptive connotation (sheeted ground) rather than a genetic one. *Blatt* was later translated as "flaw" by Miss Sollas,[11] probably as the nearest equivalent among the terms used by British miners. It is essential to an understanding of the term *Blatt* (or *flaw*) that one statement of Suess, in particular, be kept in mind.

> "The tangential movement in the earth's surface thus produces two distinct types of surfaces of discontinuity. The first group corresponds to *overthrust planes*, ..., and the second group comprises *shift planes*, 'Blätter,' (flaws) or 'Uebersprünge.' "[12]

It is evident from this straightforward statement that Suess intended "Blatt" (and flaw) to apply to a *general type of*

---

[10] Suess, E.: Das Antlitz der Erde, Band I, 1885.

[11] Suess, E.: Trans. by Sollas, The Face of the Earth, Oxford, pp. 115-121, 1904.

[12] Sollas: op. cit., p. 120.

structure and not to a structure resulting from "tangential movement" generated in any one particular way, e.g. associated only with overthrusting. Some confusion is introduced by the fact that most of the examples described by Suess are connected with overthrusting—simply because that variety of flaw furnishes the clearest and most obvious examples, the world over. This same confusion is maintained in the more recent work of Franz Suess[13] who describes in some detail the process of formation of "Blätter" using the "transversale Störung" of the Jura as an example. He does not state that "Blätter" are always formed as in the example taken, although one might easily be led to infer (wrongly) that such is the case.

Another early writer to recognize dislocations of the type under discussion was Sir Archibald Geikie,[14] who made brief mention of faults which "have been produced by a lateral thrust of one side of a fissure past the other side" and illustrated by examples from the "gneiss district of western Sutherland" in the Northwest Highlands—clearly the type of structure under discussion but no special term was proposed.

Jukes-Browne was one of the first of the British writers to offer a special term applying to faults with a large horizontal component of movement and referred to them as follows.

> "It is possible . . . that some dislocations may really be lateral shifts without any vertical displacement. These may be called *heaves* and they appear to occur in districts which have been much disturbed and fractured."[15]

At about this same time de Margerie and Heim[16] wrote at some length concerning "décrochements horizontaux," but their work does not contribute materially to the present discussion of terms.

The work of Spurr,[17] in 1896, based on observations in the Aspen district, resulted in a proposed system of naming or describing the possible *movements on faults* but was not directly concerned with naming the *resulting structures*; in fact the effect was quite the opposite, since it tended to place the discussion of faults on a primarily geometric, rather than genetic, basis. The later contributions of Tolman[18] and of Willis[19] also summarize the geometric classifications of possible fault movements but do not add greatly to the present discussion. The reason for the tendency to avoid a genetic classification is well stated by Reid,[20] who considered that for the (practical) geologist "the form of a fault is of more importance than the cause, hence the chief element for classification should be the form." This statement doubtless holds true for mining engineers and for economic geologists of that day, but can scarcely be held to apply to all geologists, particularly at the present time.

---

[13] Neumayr-Suess: Erdgeschichte, Leipzig, pp. 410-411, 1920.

[14] Geikie, A.: Text Book of Geology, 3d Ed., London, p. 584, 1893.

[15] Jukes-Browne, A. J.: Physical Geology, 2d Ed. Rev., London, p. 447, 1892.

[16] de Margerie and Heim: Les dislocations de l'ecorce terrestre, Zurich, pp. 71-76, 1888.

[17] Spurr, J. E.: U. S. G. S. Monograph No. 31, pp. 251-265, 1898.

The discussion of faulting and fault movements stimulated by Ransome[21] did, however, bring forth some suggestions concerning the naming of the structures themselves. Fairchild[22] proposed "shift (horizontal displacement)" to contrast with "fault (vertical displacement)" and Evans[23] offered "differential fault" as a similar general term, but neither has gained much subsequent recognition. Shift and shift-fault have been used occasionally in a broader sense, but not with the technical meaning which Fairchild intended.

The committee of the Geological Society of America, which studied the problem of nomenclature at some length, preferred the geometrical designation "strike-slip fault"[24] for the general type of dislocation under discussion, but also included some brief mention of "flaw" although possibly without full appreciation of the significance of the term. The committee also failed correctly to interpret Geikie's "transverse thrusts" and described the term as synonymous with "strike-slip fault" when it is actually a special subdivision of the latter general group. This mistake, made twenty years ago, has often been copied and occasionally appears in modern literature, as for example in Lindgren's *Mineral Deposits.*[25]

Leith,[26] in his recent text-book, describes faults showing horizontal movement as "heave or horizontal slip" faults, and makes a statement to the effect that the movement on the San Andreas fault ". . . is one of the few cases of directly proved horizontal displacement"—a very questionable statement in view of our present knowledge. Scott[27] also uses the general term "heave fault" and adds "horizontal fault" as a synonym. The latter term has been criticized as carrying the wrong connotation, i.e. implying a horizontal fault plane whereas the plane of such faults is actually vertical or nearly so.

---

[18] Tolman, C. F., Jr.: Econ. Geol., 2, pp. 506-511, 1907.
[19] Willis, B.: Structural Geology, N. Y., pp. 112-113, 117, 1923.
[20] Reid, J. A.: Econ. Geol., 2, p. 308, 1907.
[21] Ransome, F. L.: Econ. Geol., 1, pp. 777-787, 1906.
[22] Fairchild, H. L.: Econ. Geol., 2, pp. 184-185, 1907.
[23] Evans, J. W.: Econ. Geol., 2, pp. 805-806, 1907.
[24] Reid et al.: Bull. G. S. A., 24, pp. 176-177 and 179, 1913.
[25] Lindgren, W.: Mineral Deposits, 3d Ed., New York, p. 159, 1928.
[26] Leith, C. K.: Structural Geology, New York, pp. 84-85, 1927.

From the foregoing it will be recognized that there is no agreement on the general term to be applied to all dislocations of the kind discussed: the list of (English) terms which have been proposed includes flaw, heave, shift, heave-fault, shift-fault, slip-fault, differential fault, strike-slip fault, horizontal fault, and horizontal-slip fault, as well as dip fault and transverse fault which may be applied only in special cases. It is necessary to evaluate the terms in this list on the basis of definition, derivation, priority, and accepted usage in order to select the term or terms most suitable for future use.

Flaw, as used by Miss Sollas in translation of Suess, stands the tests of priority, definition, and to some extent accepted usage. Among the other terms, *heave* and *shift* as used in the sense originally intended by Jukes-Browne and by Fairchild have never received general acceptance: furthermore, *heave* is commonly defined as the horizontal distance between corresponding parts of a disrupted stratum, *measured at right angles to the strike*, therefore, horizontal movement *along* the strike of the fault plane cannot be called the heave and the terms *heave* and *heave-fault* have no etymological basis for use in this case.

Neither *differential* fault nor *horizontal* fault have been sufficiently accepted to deserve more than passing mention, while the terms *slip-fault* and *shift-fault* derived as they are from slip and shift, neither of which designate a direction or kind of movement, mean no more nor less than fault. Only two of the existing terms are thus left for further consideration, viz. strike-slip fault and horizontal-slip fault, although in each of these terms shift may be substituted for slip if a fault zone rather than a fault plane is described. Both *strike-slip fault* and *horizontal-slip fault* are etymologically sound terms but the former has been used much more widely than the latter. The report of the G.S.A. committee[28] on this subject is very much to the point and implies that when faulting is considered in three dimensions the three components to which the movement should be referred are; *throw* for the vertical component, *heave* for the horizontal component at right angles to the strike of the fault plane, and *strike-slip* for the horizontal component parallel with the fault plane. If a fault is to be classified as to direction of movement, the division into dip-slip, oblique-slip, and strike-slip is thence preëminently logical and the latter term is clearly applicable to dislocations of the general class under discussion. Reverse fault and normal fault are recognized as established terms for subdivisions of the first two, but neither these nor any similar subdivisions can be made for the strike-slip variety.

---

[27] Scott, W. B.: Intro. to Geol., 3d Ed., N. Y., pp. 444-446, 1932.
[28] Reid et al.: Bull. G. S. A., 24, pp. 175-178, 1913.

While the use of strike-slip fault is thus sound from the standpoint of definition and usage, and will doubtless be preferred in some cases, the term *flaw* is considered to be preferable for general use since it has the distinct merit of being a long-established and *simple* English term expressing by definition a concept comparable to and quite as broad as those implied by the terms *normal fault* or *overthrust*. In fact, a classification of dislocations in general into three groups, 1) normal faults, 2) reverse faults, and 3) flaws, has much to commend it from the standpoint of usefulness and simplicity.[29]

TEAR FAULTS.

Examples of the first class of flaws mentioned in the tentative classification, i.e. flaws genetically associated with thrusting, were apparently observed over one hundred years ago by Adam Sedgewick[30] in the Lake District of northern England, but adequate recognition of the structures was of course impossible with the limited knowledge of structural geology of that time. It is probable that other European geologists, during the following half century, likewise recognized in some degree, the character of these or similar dislocations. Eduard Suess (1885) was certainly one of the first to observe and describe examples of tear faults, but as has been noted above, his term *Blatt* (flaw) is clearly intended to express a general concept and includes not only the specific variety associated with overthrusts but all other geometrically similar structures as well. It is natural, although somewhat misleading, that most of his described examples of *Blätter* are also tear faults.

James Geikie, writing (in 1905?) shortly after Miss Sollas' translation of Suess was published, originated the terms "transcurrent fault" and "transverse thrust"[31] and his description of the origin of the structures is so clear that it is selected as the best example of its kind and worth quotation as a general description of tear faults, although under a different name.

---

[29] Suggested in part by W. H. Bucher, personal communication, March, 1933.

[30] Sedgewick, A.: Trans. Lond. Geol. Soc., 4, p. 47, 1831.

> "Transverse thrusts are obviously due to the same cause as overthrusts—tangential pressure—and may be looked upon as contemporaneous with the folds and overthrusts of the region in which they occur. When the strata of a growing mountain chain were being compressed and pushed forward in some particular direction, there might well be inequalities in the crustal creep. Some portions of the moving mass would advance more rapidly than others, and thus cause strain and tension, to which the crust would necessarily yield in the direction of the horizontal movement. The vertical fissures and fractures or glide-planes thus formed would, therefore, transverse the dominant folds and overthrusts of the chain at right angles. Transverse thrusts, it may be added, are confined to the translated rock sheets, and do not affect the rock-masses over which the latter have been driven."

The last sentence is especially significant, since some modern writers have failed to appreciate the point made.

Another excellent description of the phenomenon is that given by T. C. Chamberlin[32] in which "transcurrent" fault, "Blätt," and "flaw" are all mentioned although not considered to be synonymous (footnote). Chamberlin was one of very few writers to recognize the latter point, but did not attempt to clarify the nomenclature.

The term *tear fault* was used, and presumably introduced, by the British geologist Marr, in 1906,[33] in describing the same type of structure as Geikie's *transverse thrusts.* The same writer later gave a good illustration of the use of the term in his description of the structure of the English Lake District.[34] The British use of *tear fault*, which is now quite general, is somewhat paralleled by De Lapparent's use of "déchirures"[35] (from the verb meaning to tear) in describing the transverse fractures of the Alps and the Jura, although he otherwise writes of these in general terms as "les coupures transversales des Alpes" or "les accidents transversaux." The fractures referred to are the same ones described by Franz Suess under the general term *Blätt,* and recently by Collet[36] as *tear faults,* so that an interesting comparison of terms is thus made possible.

---

[31] Geikie, J.: Structural and Field Geology, 3d Ed. Rev., New York, pp. 179-180, 1912.

[32] Chamberlin, T. C.: Econ. Geol., 2, pp. 590-591, 1907.

[33] Marr, J. E.: Q. J. G. S., Proc. p. lxxvi, 1906.

[34] Marr, J. E.: Geol. of the Lake District, Camb., pp. 69-71, 1916.

[35] DeLapparent, A.: Traité de Geologie, 5th Ed., Paris, pp. 1861 and 1872, 1906.

Within the last few years the term *tear fault* has been adopted and used by several American geologists, although examples of this structure under any term are not common in the American literature. Longwell, in his early descriptions of the Arrowhead fault[37] in the Muddy Mountains of Nevada, compares it with the "transcurrent faults or flaws of the Alps" and later in further describing the same phenomenon uses "Blätt," "flaw," and "tear fault"[38] but without indicating a preference. The use of so many terms to describe a single structure indicates very well the lack of an accepted nomenclature. More recently, Billings[39] has described the occurrence of several tear faults in the Boston basin, and Lovering[40] has discussed the importance of tear faults in distinguishing between overthrusting and underthrusting as shown by examples from the Southern and Middle Rockies. Incidentally, several other examples of tear faults are known from this general region. The use of *tear fault* by these representative authors (and others), when considered together with the subordinate use of synonymous terms, is interpreted as sanctioning its use in modern geologic literature and it is now, in the writer's opinion, more suitable than *transverse thrust* which carries a somewhat inappropriate connotation, although it is well defined and has some claim to priority.

Keyes has published an extensive criticism of the nomenclature under discussion and has offered a new term, "shear-fault."[41] The value of this new term is dependent upon the validity of Keyes' criticism of the adequacy of existing terms, and as this is very questionable in the opinion of the present writer, the use of "shear-fault" would merely introduce further unnecessary complication. Incidentally, "shear-fault" is subject to possible confusion with "shear-thrust" (since both are connected with thrusting) a term introduced by Willis,[42] in his well-known classification, to designate one of the common types of overthrusts and which is still in present use.[43]

---

[36] Collet, Leon: Structure of the Alps, London, pp. 15, 121-122, 143-144, and 146, 1927.

[37] Longwell, C. R.: Bull. G. S. A., **35**, p. 64 (abst.), 1924.

[38] Longwell, C. R.: Bull. G. S. A., **37**, p. 572, 1926.

[39] Billings, M.: this Journal, **18**, pp. 127-130, 1929.

[40] Lovering, T. S.: Jour. Geol., **40**, pp. 651-663, 1932.

[41] Keyes, C. R.: Pan. Amer. Geol., **57**, pp. 202-207, 1932.

[42] Willis, B.: 13th Ann. Rept. U. S. G. S., Part II, pp. 222-223, 1893.

One very questionable use of ***tear fault*** in the modern literature is that made by Nevin,[44] in which the San Andreas fault is taken as a type and is the only example mentioned by him in his description of the term. The mechanics involved in the movements on the San Andreas fault and associated structures have been discussed by Vickery[45] (and other writers) and it seems yet to be demonstrated that the San Andreas fault is related to overthrusting, especially in the sense necessarily implied by the term ***tear fault*** in its properly restricted meaning.

SUMMARY.

It is recommended that any dislocation characterized by dominant horizontal movement along an essentially vertical plane be designated as a ***flaw***, although the term ***strike-slip fault*** is recognized as a permissible alternative. *Flaw* is complementary to, and of equal rank with, the terms ***normal fault*** and ***reverse fault*** in a classification of dislocations in general.

Flaws are shown to be of several genetic varieties of which the flaws formed by differential movements within a thrust block are most important and are best designated by the British term ***tear fault***. Other recognized varieties of flaws are those formed by crustal adjustment incidental to igneous intrusion and those of the San Andreas type, the exact origin of which is but imperfectly known. It is probable that additional varieties of flaws will be recognized and catalogued as such structures are further studied in the light of a genetic classification.

Williams College,
Williamstown, Mass.

---

[43] Billings, M.: this Journal, 5th Ser., 25, p. 142, 1933.
[44] Nevin, C. M.: Structural Geology, New York, pp. 93-94, 1931.
[45] Vickery, F. P.: Jour. Geol., 33, pp. 608-628, 1925.

A PRELIMINARY NOTICE ON THE MIOCENE AND PLIOCENE MAMMALIAN FAUNAS NEAR VALENTINE, NEBRASKA.

R. A. STIRTON AND PAUL O. McGREW.

The first fossils known from the vicinity of Valentine, Nebraska, were those described by Joseph Leidy in 1858. Since that time numerous species have been described from the region, and for the most part were called upper Miocene in age, but some authors recognized Pliocene fossils in their collections and either referred to them as lower Pliocene or Mio-Pliocene faunas.

A University of California party worked on the Niobrara Game Preserve in the summer of 1933 for the purpose of collecting from the different horizons and if possible to determine the age of the material found at each level. In the fall of that year McGrew collected some faunas from Snake River and Gordon Creek; additions to these were made in 1934. The work in this region was facilitated by our association with Dr. Maxim K. Elias of the University of Kansas, who succeeded in locating plant-seed zones which he had found so widespread in the Ogalalla formation.

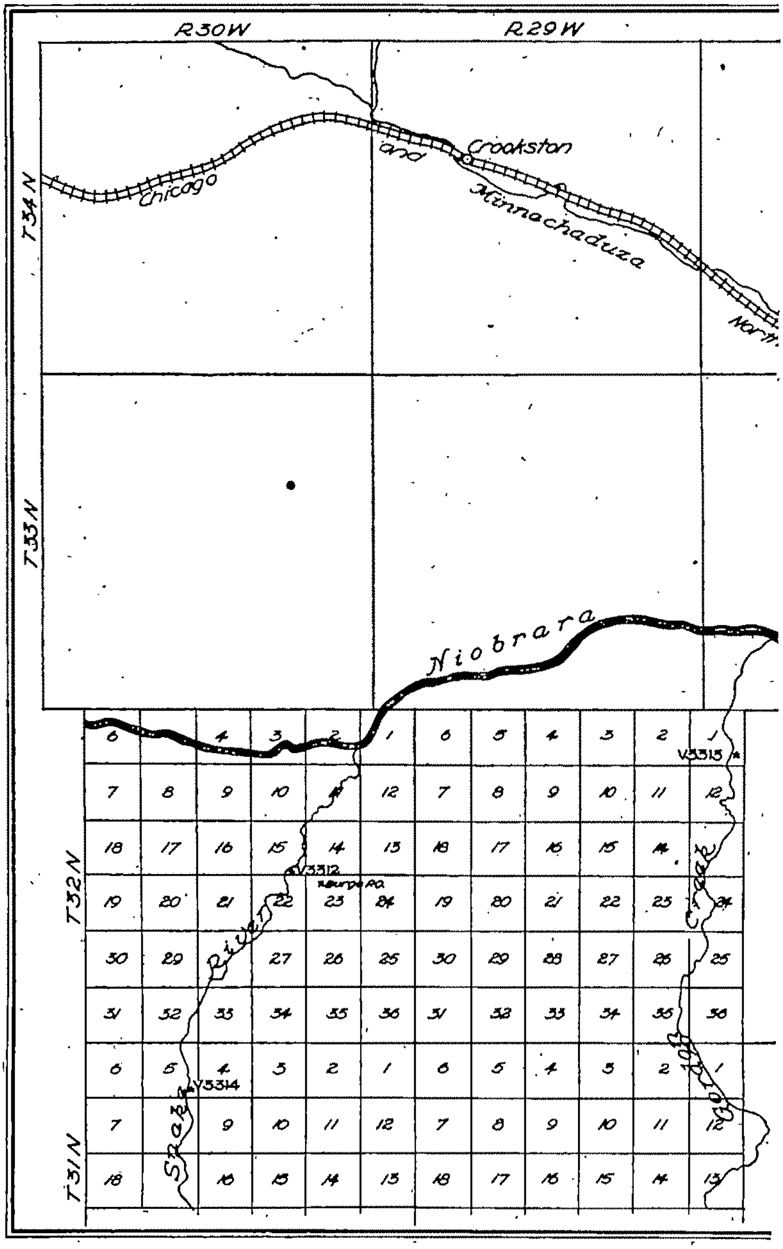
The purpose of this paper is to show the definite position of our faunal localities, both geographically and stratigraphically, and to determine their age.

We wish to express our gratitude to Dr. E. H. Barbour and members of the Nebraska State Museum for their coöperation and assistance. We also recognize with thanks the generous hospitality and aid extended us by Mr. Geno A. Amundson of the Niobrara Game Preserve.

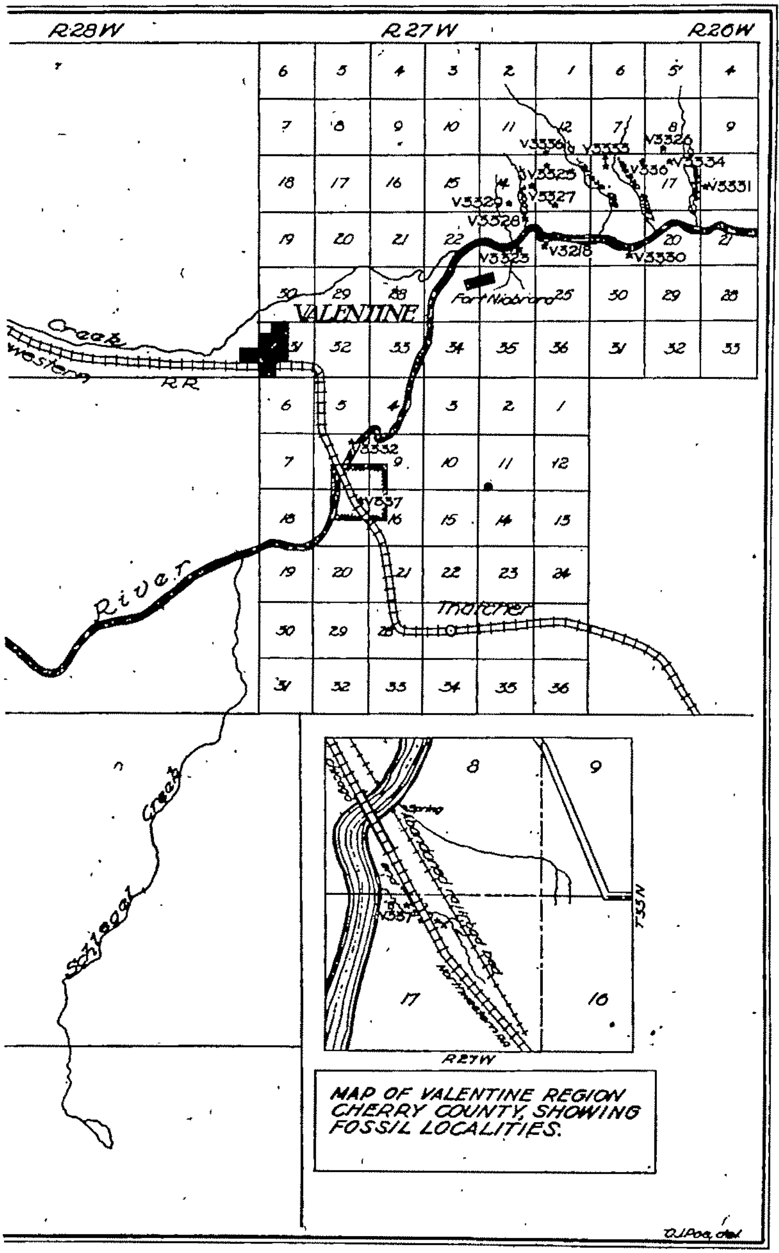
APPLICATION OF FAUNAL NAMES.

We have applied a faunal name to those collections of fossil vertebrates which agree, so far as can be determined, in their generic and specific characters. These faunal names should not be used in any stratigraphic sense. Much confusion has been caused in the past by giving faunal names formational significance. This is well exemplified in the Valentine region where three faunas representing two epochs occur in one formation.

The formation with which we are dealing is well exposed



The sections from the Valentine and Niobrara River faunal localities were made by M. K. Elias in 1933 and checked by Stirton. The Burge sections were made by McGrew.



MAP OF VALENTINE REGION CHERRY COUNTY, SHOWING FOSSIL LOCALITIES.

along the Niobrara River and its tributaries from Valentine west, at least as far as Hay Springs. Lithologically, this formation is not unlike the Ogalalla farther south, and although it may be the same formation no one has definitely traced it through the sand hills of middle Nebraska. In South Dakota it is comparable to the exposures along the Little White River which were mentioned and briefly discussed by Matthew and Gidley (1904) in their description of "New and little known mammals from South Dakota." Near Valentine this formation rests unconformably on a reddish, slightly banded, loessic formation which Matthew considered lower Miocene.

We were unable to use stratigraphic and lithologic evidence when dealing with the faunas which occur in stream-channel deposits. The lithology of some of these channels agrees superficially with that of others but they are found to contain fossils of different age. The more indurated, calcareous sands near the top of the section can be traced over a large area, but west of Valentine we were not able to find fossils to check the correlation.

NIOBRARA RIVER FAUNA.

In his first reports on the fossils from Nebraska, Leidy referred to this fauna as coming "from the sands of the Niobrara River." After one has collected in the region of the old Fort Niobrara (now the Niobrara Game Preserve) it is clear that Hayden found most of his fossils in the loose, unconsolidated sands of the upper Miocene horizon where we found our Niobrara River fauna. Barbour and Cook (1917) described a skull of *Aelurodon platyrhinus* from this fauna and referred to the horizon as the Valentine beds. Subsequently specimens from this fauna and others from the Pliocene were referred to as the Valentine fauna. Osborn (1918) called them the Fort Niobrara fauna but Valentine was the name that became most widely used (Thorpe, 1922). We propose to use Leidy's original terminology (Niobrara River) for this upper Miocene fauna.

The Niobrara River fauna is usually found in the channel sands about seventy to one hundred feet above the ?lower Miocene formation. We found three exposures on the Niobrara Game Preserve that yielded fossils for our faunal lists, but most of these specimens were found on the surface and not in place. An *Alticamelus* skull which was found at locality

V3336 probably belongs to the fauna. The best representation of the fauna is from the old *Aleurodon platyrhinus* quarry (UC. Loc. V337). This collection is in the Nebraska State Museum. There is some suggestion from locality V3323 that a fauna from the lower part of the section may be the equivalent of the Mascall. Although we have called the Niobrara River an upper Miocene fauna, it is practically transitional between the upper Miocene and lower Pliocene, but nearer to the Miocene than to the Pliocene.

FAUNAL LISTS

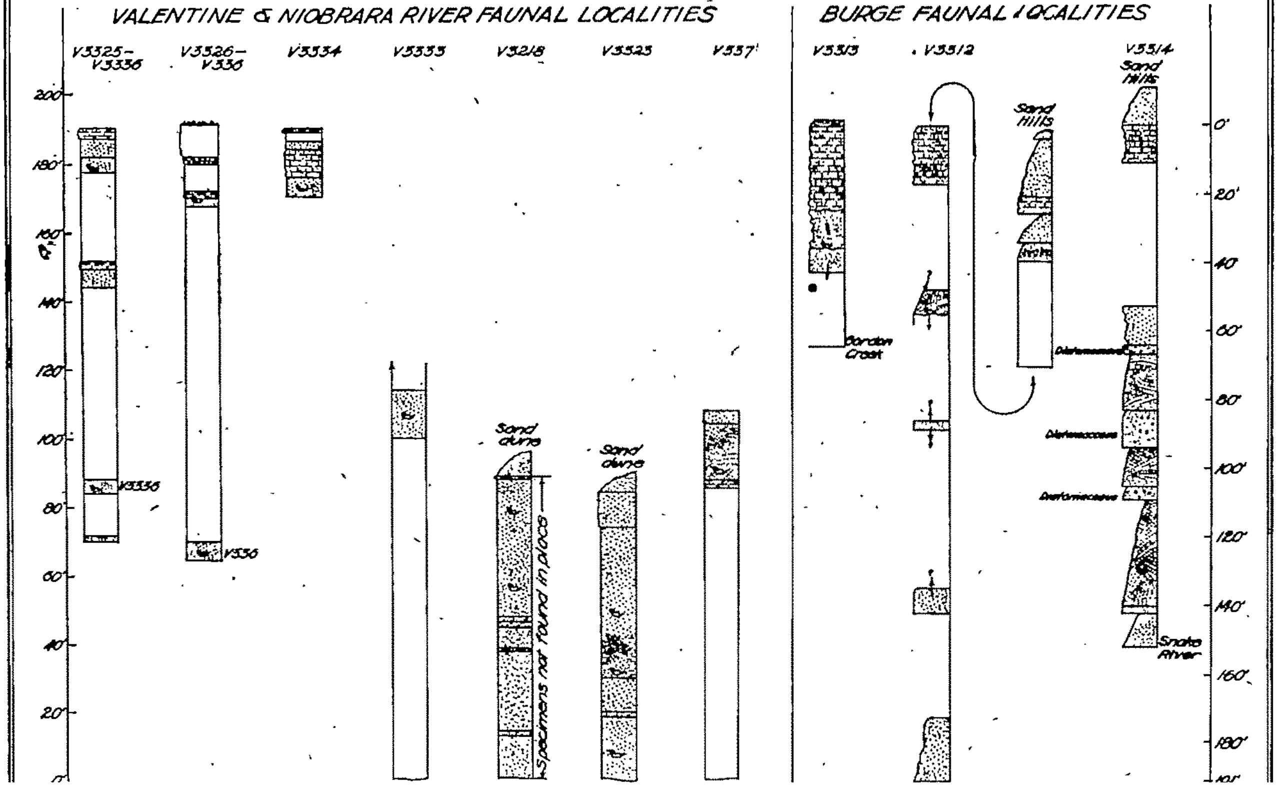
Loc. V3218	Loc. V336	Loc. V3323
Metechinus		
Talpidae		
Mookomys altifluminus		
Mylagaulus		
*Monosaulax**	*Monosaulax**	
Lagomorpha	Lagomorpha	
?Tomarctus		
Vulpes vafer	*Vulpes vafer*	
Bassariscus antiquus		
Pseudaelurus		
Mustelidae		
Proboscidea		Mastodontinae
Hypohippus	*Hypohippus affinis*	
Merychippus		*Merychippus*
Prosthennops		
Camelidae		Camelidae
Blastomeryx		
Merycodus	*Merycodus*	*Merycodus*

* The description of Monosaulax is in press.

BURGE FAUNA.

The collections made by McGrew in channel sands near the Burge postoffice on the Snake River and the one from Gordon Creek are the only collections in the Valentine region that we have called lower Pliocene. Possibly some of the miscellaneous finds that have been described from the "Valentine Beds" belong to this fauna, but at present we have not recognized them. The Burge fauna appears to be the equivalent of the Esmeralda of Nevada and is probably contemporaneous with the Clarendon of Texas.

SCALE SECTIONS AT THE FOSSIL LOCALITIES IN THE VALENTINE AREA, NEBRASKA



FAUNAL LISTS

Loc. V3312	Loc. V3314	Loc. V3313
		Erinaceidae
Mylagaulus		
?*Eucastor*	*Eucastor*	Castoridae
Cynodesmus sp. nov.		*Cynodesmus* sp.
Aelurodon		
	Vulpes vafer	
cf. *Sthenictis*		
Mastodontinae	Mastodontinae	Mastodontinae
Hypohippus affinis	*Hypohippus*	*Hypohippus affinis*
Merychippus		
Pliohippus		*Pliohippus*
Nannippus	*Nannippus*	*Nannippus*
Neohipparion		*Neohipparion*
Prosthennops		
		Oreodontidae
Procamelus	*Procamelus*	*Procamelus*
Alticamelus	?*Alticamelus* cf. *altus*	
Blastomeryx		
Dromomeryx		*Dromomeryx*
Merycodus	*Merycodus*	*Merycodus*

VALENTINE FAUNA.

The name Valentine has become so widely known that we have used it to designate our Pliocene fauna from the calcareous sands in the upper part of the section on the Niobrara Game Preserve. Although the fauna is not complete, it shows certain species that intergrade between the lower Pliocene and middle Pliocene. It marks the termination of most of the genera that carry over from the upper Miocene, and the first appearance of certain genera and species that are so characteristic of middle Pliocene faunas. For this reason we have considered the Valentine as transitional from lower to middle Pliocene.

FAUNAL LISTS

Loc. V3326	Loc. V3334	Loc. V3327	Loc. V3329	Loc. V332
				Talpidae
				Castoridae
?*Pliocyon*			Amphicyoninae	*Hadrocyon*
Leptarctus.				
Felidae		*Pseudaelurus*		Felidae
Teleoceras		*Teleoceras*		*Teleoceras*
Hypohippus	*Hypohippus*			
H. matthewi				
Pliohippus				*Pliohippus*
Neohipparion	*Neohipparion*	*Neohipparion*		*Neohipparion*
Nannippus	*Nannippus*		*Nannippus*	*Nannippus*
				Oreodontidae
?*Procamelus*	Camelidae	Camelidae	Camelidae	Camelidae
Alticamelus				
Megatylobus				

MISCELLANEOUS LOCALITIES.

There are five localities on the map that are not included in the faunas listed above. The age of the material from these localities is only tentatively identified.

Loc. V3328—*Merychippus*—upper Miocene.
Loc. V3330—?*Merychippus*, ?*Neohipparion*, ?*Equus*, Antilocapridae, *Elephas*—faunas mixed—Miocene, Pliocene, Pleistocene.
Loc. V3331—*Pliohippus*—Pliocene.
Loc. V3332—Mastodontinae, ?*Neotragoceras*—?upper Miocene.
Loc. V3333—Rhinoceratidae, Camelidae, Antilocapridae—?age.

SUMMARY.

Three late Tertiary faunas representing two epochs were found in one formation near Valentine, Nebraska, and the following faunal names have been applied: Niobrara River—upper Miocene; Burge—lower Pliocene; Valentine—transitional from lower to middle Pliocene. Faunal localities are located both geographically and stratigraphically, and faunal lists are given from each locality.

LITERATURE CITED.

Barbour, E. H., and Harold J. Cook: Skull of *Aleurodon platyrhinus*, sp. nov. Neb. Geol. Surv., vol. 7, pp. 173-180, 1917.

Leidy, J.: Notice of remains of extinct vertebrata from the valley of the Niobrara River collected . . . . . . Proc. Acad. Nat. Sci. Phila., vol. 10, pp. 20-29, 1858.

Matthew, W. D., and J. W. Gidley: New or little known mammals from the Miocene of South Dakota. Bull. Amer. Mus. Nat. Hist., vol. 20, pp. 241-268, 1904.

Osborn, H. F.: Equidae of the Oligocene, Miocene, and Pliocene of North America, Iconographic type revision. Mem. Amer. Mus. Nat. Hist., vol. 2, pp. 1-217, 1918.

Thorpe, M. R.: Some Tertiary Carnivora in the Marsh collection with descriptions of new forms. This Journal, vol. 3, pp. 423-455, 1922.

MUSEUM OF PALEONTOLOGY,
UNIVERSITY OF CALIFORNIA,
BERKELEY, CALIFORNIA.

WHAT IS "POCONO"?

GEORGE HALCOTT CHADWICK.

INTRODUCTION.

To those of us who know and love David White, his return to health as shown by his recent paper[1] in this Journal is a source of rejoicing. It is in no sense of controversy, then, that I am replying to it, but merely to point out that perhaps, indeed almost admittedly, we have been talking of different things, that there is no real issue between us.

Doctor White comes to the defense of the venerable name "Pocono" (I say "venerable" because it is just my own age!), but the whole matter seems to revolve itself around the question: "What *is* Pocono?" In attempting to unravel this, the accompanying map (Fig. 1) will be found helpful. This map shows, though crudely, the area of Pennsylvania occupied, more or less interruptedly, by the Pennsylvanian strata beginning with the Pottsville conglomerate. On the south and east, the Pottsville limit is the unbroken line as shown; but on the north and west it is far more ragged than would be profitable to represent it. There the mapped boundary merely encloses the larger and less widely sundered remnants (as does that on the new official map of the United States, though differently), omitting the smaller, scattered patches, and neglecting also the spiderweb of dissecting stream courses reaching far back into the embed especially across the counties of Clinton, Cameron, Elk, Forest and Venango. In the southwest are omitted the numerous inliers of lower strata threaded along the occasional anticlinal axes west of the Allegheny front, except one at Patton and one in Fayette county to which reference will be made.

Care has been taken, however, not to omit any of the tiny outlying patches of the Pennsylvanian intervening between the bituminous fields and the eastern anthracite synclines, because here there is a gap of noteworthy span, bridged only imperfectly by the Bernice and neighboring coal-basins. Outside the Pennsylvanian areas and in general rimming them rather closely, is the strip of outcrop of the beds mapped in the state reports as Pocono and Mauch Chunk. Unless one realizes that there is a known hiatus and a respectable uncon-

---

[1] The Age of the Pocono, this Journal (No. 160) 27, 265-272, April, 1934. Compare abstract printed for Chicago meeting Geol. Soc. Amer. 46, 52-53, Dec., 1933, which thesis is accepted by me without question, save the use of the name Pocono.

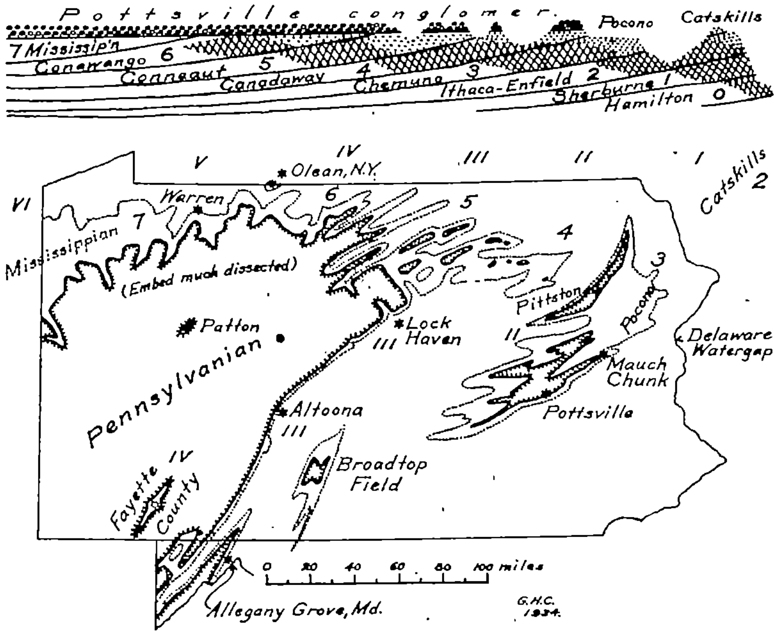


Fig. 1. *Outline Map of Pennsylvania, from County Maps,* showing outer limits of basal Pennsylvanian (Pottsville conglomerate) in solid fringed line, and outer limit of beds mapped as "Pocono" and "Mauch Chunk" in dotted line. Northern frayed margins of each greatly simplified. Numerous inliers in southwest mostly omitted.

Above: Rough stratigraphic diagram showing in vertical section the relations, along the northern margin, of the Devonian and Mississippian strata to the base of the Pottsville (circles) as horizontal datum. Does not depict present topography and structure. Red-beds ("Catskill" facies) cross-hatched; "white" beds ("Pocono" facies) dotted.

Numbers (arabic on diagram, roman on map) denote successive marine faunas: 0, Hamilton; 1, Genesee (Sherburne); 2, Naples (Ithaca-Enfield); 3, true Chemung (including type Portage); 4, Canadaway (Dunkirk-Northeast); 5, Conneaut (Girard-Chadakoin); 6, Bradfordian (Conewango-Knapp); 7, Post-Devonic (Waverly). On the map, the arabic numerals indicate corresponding age of the beds called "Pocono." (There is no actual "Mauch Chunk" on the north outcrop.)

formity (disconformity) at the base of the Pottsville, such a map gives one a distinct sense of satisfaction as to the identity and continuity of these reputed Pocono and Mauch Chunk strata clear around the State, a confidence somewhat weakened, however, if the two are mapped separately and thus the actual failure of the "Mauch Chunk" along the northern border revealed to the eye (though the figment of its presence there is preserved on many a county map!). On the other hand, still further strengthening of the illusion would result if, instead, the belt of underlying red "Catskill" were added to the map. It has taken nearly a century of field work, including fifteen years of my own best efforts, to disclose the fallacies resident in this too "obviously simple" stratigraphy, to convince even myself that it is all wrong, for I went into the field believing it was all *right*. Doubtless it will take years still of confirmatory work by others to gain general acceptance of the truths at length so evident to a comparative few of us.

It must be emphasized that this exploration has been confined to the northern and eastern parts of the State, from Lake Erie to the Delaware River and down that to the Watergap, and that my published determinations refer to that region, not to the south and west portions. The Lehigh section (past Mauch Chunk) I have not seen, except from the train. Nor have I gone south of Lock Haven on the Allegheny front. What happens thence is another story, yet to be reinvestigated. I have no present disposition to deny any of the published interpretations of it, and I have the greatest confidence in Doctor White's knowledge and understanding of the area. I would like him, and all, to have confidence in my understanding of a different area that he concedes I know more intimately than he. My assertions have been provocative, it was inevitable that they should be challenged, and should require the defense that I will now undertake by presenting a small though significant part of the accumulated evidence.

THE NORTH OUTCROP.

The dwindling edge of the Mississippian (Waverly) beds of Ohio enters Pennsylvania at the northwest (see Fig. 1, map and section) and continues east, according to Caster, as far as the meridian of Olean, N. Y. (Smethport, Pa.); though in a paper now ready for publication[2] I have incidentally shown faunal reasons for terminating the Waverly wedge short of this, near Warren, Pa. In any case, at Olean at least, the Upper Devonian marine fossils and strata come right up to the base of the Pottsville and preclude any Mississippian. Thence eastward no Waverly fossils appear; but the sub-Pottsville strata shortly become continental while the Devonian marine fossils fall away from the contact down to lower levels.

---

[2] Faunal Differentiation in the Upper Devonian, abstract in same meeting, **46**, 82-83.

Now far from this marking a return of Mississippian (supposed Pocono) strata, as I with others once believed, the later stratigraphic tracing, fully corroborated to-day by the recent faunal studies just mentioned, shows a very different state of affairs. It shows that the marine strata and fossils present beneath the continental beds at this point are of an older epoch (Chautauquan) than those (Bradfordian) that we have just left at west, and thenceforward of progressively older groups (and epochs) as we proceed on eastward. Indeed, the number of such faunas (and groups) has only within a few months become evident, the name "Chemung" having obfuscated the facts. All told, beneath the continental beds there lie in succession, eastward, six increasingly older (lower) marine faunas that in turn hold the stage of the New York Upper Devonic, which laps into northern Pennsylvania.

With the names and details of these faunas, so soon to be published, we are not here concerned, but only with the broad proofs they furnish and with the fact of their distinctness. No one will be disposed to quarrel with the eastern half of them, namely (see the figure) the Hamilton below, and then the Genesee (Sherburne), Naples (Ithaca-Enfield) and the true Chemung. But it will come as a surprise to many that these do not differ so much among themselves, faunally, as does the true Chemung from the next succeeding group above it, the Canadaway, called "Chemung" on the Genesee River. The latest count shows 250 true Chemung species failing to cross this line (Senecan to Chautauquan, as now understood) into the Canadaway as against only 90, mostly long range, forms that do, and in their place 135 new species with a dozen striking new genera appearing for the first time above this dividing line, which corresponds westward with the top of the old (type) Portage. The next faunal break, that at the Cuba sandstone, is no new discovery, while the distinction of the sixth and last, or Bradfordian (Conewango, plus probably Knapp and so-called "Berea" of Warren area) fauna, is a part of our obligation to Doctor Girty, whom Doctor White quotes, and to Mr. Butts and Professor Williams.

Now the essential point is that each of these faunas, in turn coming in, rises eastward toward the transcending Pottsville base (see the section in Fig. 1), crowding up against it the Devonian remnants (continental beds) that still overlie, and these are thus seen to be steadily bevelled off, eastward, by the summit unconformity against the Pottsville, just as already and indisputably[3] the Mississippian Waverly beds have been similarly pared off and out from top downward in coming east across and from Ohio. But this means that the (distinctly heterogeneous[4]) bits of the geologic column which happen locally to underlie directly the Pottsville, and are, therefore, always classified as "Pocono" on this northern outcrop though at times they may be largely red (as in the Le Roy or "South Mountain" section of Williams & Kindle), are actually as different as they look and belong to increasingly older divisions as we proceed east.

In fact, and this is not inference but can be demonstrated to anyone in the field while snatches of it have long been recorded in the literature, each of these six Upper Devonian divisions or groups, traced eastward, passes into red-beds called "Catskill," and each traced westward passes into less prolific beds called "Portage," thus giving rise through progressive overlap to the false appearance of horizontal continuity of each such facies (see the diagram) and to the deceptive resemblance of their vertical sequence on different meridians. Traced still farther east, and this again is not inference but has been seen and noted by others, especially by H. Martyn Chance,[5] each "red" in turn loses its red shale content while its olive flags persist and are called "Pocono." It is evident that the "Pocono" sands and gravels were deposited farther up the delta slope where the red muds did not so easily find lodgment.

These relations are indicated on the map by the arabic figures adjacent to the northern "Pocono" outcrop, the numbers denoting the age of the supra-"Catskill" beds in a given sector with reference to the contemporaneous marine fauna as numbered in the section-diagram, and as, for distinction, located on the map in outcrop by means of corresponding Roman numerals.

---

[3] Butts, Charles, Pre-Pennsylvanian Stratigraphy, Rp. Top. Geol. Sur. Pa. 1906-8, 191, 194-195, fig. 18, and Pls. VIII, IX (fig. 2), 1908. Description of the Warren Quadrangle, U. S. G. S. Fol. 172, 37-38, 1910.

[4] See the county reports and Lesley, J. P., Summary Final Report (1895), 3, 1635-1651 (especially 1643), 1717-1779 (especially 1727, 1729), and 1821. For the still more diversified "Mauch Chunk," see pages 1815-1823, 1829, 1833-1840. Lesley's volumes have been at my elbow, and often consulted, but while the lovableness of their writer appears all through them, so too often does his personal viewpoint obscure facts better seen and presented (when permitted) by his assistants in their individual reports. The faulty generalization about the Pocono in the paragraph on pages 1651-3, for example, seems to have misled even Doctor White as to its physiographic continuity.

[5] Lesley, *Ibid.*, 1727; Chance, H. M., Pa. 2d G. S. **G4**, 114 *et ante*, 1880.

It will be seen that herein lies the explanation of the enormous and erratic variations reported in the thickness of the "Pocono" on this north outcrop—from nothing at Olean to "1000 feet" at Gaines (Fuller) down to 400 feet in Armenia mountain (Rogers) and so on,—and also of the puzzles over "transition beds" that afflicted I. C. White and others, and of why the "Pocono" (Bradfordian) at Port Allegany furnished to Arnold specimens of *Archaeopteris*, which Doctor White confirms us as a strictly Devonian genus, and again to Sherwood near Mansfield (from the Canadaway "Pocono") the types of *Gyracanthus sherwoodi*, an upper Upper Devonian fish species. It will explain, too, why I said that land-plants, less common, in the "Pocono" are not known to differ from "Catskill" forms, to which statement Doctor White, speaking and thinking of an entirely different area and a different set of strata, objects. He, too, is right.

And that brings us back to the real question: "What is Pocono?," which will now be seen to be a matter of definition based on the type locality, as was the companion question: "What is Catskill?" discussed by me last fall in this Journal.[6] But there is this difference in the two cases, that whereas Mather gave us a meticulously detailed and delimited section along a known highway for his Catskill, we are left to hunt high and low for any type section or precise geographic localization of the geologic name Pocono. It is clear that Doctor White's guess as to what is type Pocono is therefore as good as mine, and that, since I spent two pages (104-105, pages which he does not quote or mention) in explaining this mix-up and how according to I. C. White's report[7] there is *no* Pocono in Pocono Mountain (Pocono Knob) or Pocono township, or in fact on the whole Pocono plateau except topping a few isolated peaks far back from the scarp though all this was misrepresented by Lesley on White's map for (Lesley says) physiographic reasons, there can therefore be no "beds regarded by him [me] as the type section of the Pocono." I am still waiting for someone, and I have asked several people in a position to know, to locate and define this type section of the Pocono, for I do not feel competent to do so. If it is up the face of Pocono Knob, then according to I. C. White it is all "Catskill," Devonian. If it is bottomed on the Griswold Gap conglomerate, as the same author thought in 1881, then there is none of it within miles of the Pocono plateau and, as I have intimated, it should be called Moosic. If it includes, as he decided in 1882, also the 375 feet of his "Pocono-Catskill transition beds" down to the base of the Mount Pleasant conglomerate, then the latter (he says) just grazes the tops of the highest monadnocks on the Poconos, so the name is equally inappropriate. What *is* Pocono?

---

[6] Catskill as a Geologic Name, this Journal **26**, 479-484, Nov., 1933. Subsequent recognition of the identity of the Chemung with the Portage (Abstracts for Chicago meeting G. S. A., **46**, 18-19, 1933) shows that the Blossburg reds are Canadaway, not Conneaut (Girard-Chadakoin), so that the reds of Conneaut age remain nameless.

[7] Pa. 2d G. S., **G6**, 89-90, 1882.

On the map (Fig. 1) I have followed Lesley in spreading the Pocono limit eastward around the entire plateau (no other mapping is available!), and this line unquestionably embraces beds of Upper Devonian age and unquestionably no higher than true Chemung strata (3), since a trace of the Kattel (lower Enfield) fauna occurs not far below, in the midst of red-beds. Let us grant as entirely possible that "in passing around the elbow" I may have "failed to contact the true Pocono," but what *is* this true Pocono? Is it the Moosic, which I will admit may be post-Chemung (Canadaway) from the Griswold Gap conglomerate up (see the section-diagram)? Or something on the Lehigh at (East) Mauch Chunk, which is not (see the U. S. G. S. topographic maps) "on the slope of the Pocono Mountains" nor even on that of their extension the Pohopoko, but on the separate syncline of Big Creek Mountain? Here is the problem of nomenclature that confronts me, and I think also Doctor White. Who will solve it?

I suspect it is almost safe to assume that, in common with geologists generally, Doctor White has really been, quite naturally, projecting his idea of what he says he regards "as the typical . . . Pocono" from the fossiliferous strata as far away as the Broadtop field, a procedure of which our just narrated experience along the north outcrop would tend to make us wary. But to avoid quibbling over names, and since, although in crossing the northern anthracite syncline from Carbondale and Scranton and Wilkesbarre to the Poconos I may have passed unrecognized an entering wedge of Mississippian coming up from the south, I have nevertheless claimed

Devonian age for all the beds on the east limb of this syncline (at Carbondale, the north end) "right up to the base of the Pottsville," I pass on east (see Fig. 1) to the confirmatory evidence afforded by the Catskill Mountains. Here, according to Lesley in the summary report which Doctor White thinks unfamiliar to most geologists (page 1567), the Pocono (Lesley says) forms approximately the upper 1,000 feet of the peaks. Such a conglomerate indeed constitutes the thousand feet and more of the summit of Wittenberg, where it is best exposed, and others of the high central Catskills, but it is easy to show by direct tracing that this Wittenberg conglomerate is upper Enfield, equivalent to upper part of the Hatch shale of western New York, of Naples age (2). Above it, capping only the one highest pinnacle of the Castkills, is the thinner Slide Mountain conglomerate, corresponding apparently to the Grimes sandstone or basal bed of the Chemung, and thus perhaps to the base of the typical Pocono or lower. In the most easterly peaks of the Catskills, moreover, come in yet lower puddingstones, not much above the top of the Hamilton, thus completing that orderly downward progress of the Pocono facies eastward of which the Pocono region proper appears to form an integral part. A series of carefully measured sections in the Catskills is about ready for publication.

THE SOUTH OUTCROP.

Now what happens on the south outcrop, or that which Doctor White prefers to call the eastern? Looking again at the map (Fig. 1), I doubt whether he meant to leave the impression that the Pocono can be traced as an uninterrupted scarp from East Mauch Chunk into Maryland. The visible gap is far too considerable nor is the course a direct one. In the jump back to Lock Haven, indeed, the "Mauch Chunk" so nearly fails of expression ("thins away to nothing 2 miles west of Lock Haven," says Lesley, summary report page 1837) that the "Pocono" there has no individual scarp but unites with the Pottsville above it. If a "Pocono" scarp picks up again farther south, with a red shale incoming and thickening above it, I would wish more than physiographic existence to predicate chronologic identity with the Pocono and Mauch Chunk of the eastern synclines (anthracite basins). For the great red shale that has thinned from 3,000 feet in the southern anthracite area (Pottsville region) to a doubtful 150 feet of beds *not red* (Lesley, summary, page 1827) at Pittston has then to cross a gap of over one hundred miles in which every scattered identification of it falls under suspicion as only some accidental encounter of one of the red shales within the "Pocono," in the diagonally eroded top of the latter, before resuming an unbroken course beyond Lock Haven, with a thickness seldom exceeding 300 feet.

Yet with 1,100 feet of this red in the Broadtop field, the identity of the red Mauch Chunk shale seems reasonably assured from Lock Haven and near Pittston southward, and I am prepared to compromise to the extent of admitting Mississippian age of at least its upper portion at the type locality, Mauch Chunk, though I still lack any direct paleontological proof of this at that spot, which is all that I have positively asserted with regard to it. Can Doctor White supply the "smitch of evidence" from, or sufficiently near, Mauch Chunk that I said was wanting? Does the *Triphyllopteris* flora reach eastward into the anthracite basins? He can give us no more welcome help with these problems than to have prepared and printed a complete catalogue of all the known "Pocono" and Mauch Chunk fossils on this south sector across Pennsylvania, with the precise localities from which each has been obtained or reported.

Referring, however, to the unusual marine fossils from the Broadtop field, nearly 150 miles distant from Pocono Knob, of which Doctor White says that they were "assigned by Dr. George H. Girty to the lower Mississippian" in Professional Paper 150-E, my reading of Doctor Girty's interpretations has not been so unqualified. Remembering that the latter came to the study of this fauna with the preconception that its source beds were stratigraphically Mississippian, and that his specific comparisons and identifications are therefore naturally with Mississippian rather than Devonian forms, one marks his hesitation (page 112, especially second column) whether the fauna really is Carboniferous and not Devonian. Save *Scaphiocrinus*, a generic reference not vigorously supported in the text and leaving one to wonder whether one of the Devonian genera of the Poteriocrinidae will not do as well, and *Stenopora*? (admittedly perhaps *Leioclema*) and possibly *Cytherellina*? of whose range I am uncertain, the genera listed are those that dominate the Upper Devonian though known also in the Waverly. Yet I found that to have to fit such a fossiliferous horizon into the Devonian sequence at this level here would prove most inconvenient, and I raise the point only to put Doctor White on his guard in citing it as evidence.

What I do know, very definitely, with regard to this southern outcrop, is the age of the highest marine faunas next below the red-beds called "Catskill" at four critical points. At Altoona and Lock Haven these are Chemung, as would be expected, and at Catawissa, intermediate between Lock Haven and Mauch Chunk, they are Enfield, as would also be anticipated. But the interesting thing is that in Fayette county, contrary to a recent published determination,[8] they are definitely post-Chemung, Canadaway, though it must be said in extenuation that this faunal distinction had not yet been worked out in New York when Doctor Willard's paper appeared. Thus the marine Devonian beds (as marked by Roman numerals) are "running true to form" into Maryland, where at Allegany Grove we have the Canadaway (4) fauna with *Athyris angelica* wedging in still farther east than Fayette county.

THE RETORT COURTEOUS.

I do not know where Doctor White got the idea that I had made mention of Patton[9] (his page 271), unless he means someone else has, for I have had to look up its location though familiar with the fact that a Patton red shale is recognized in wells of that region; yet I am glad he introduces this confirmation of the summit erosion-plane. But when he accuses me of never having even heard of those old friends the Greenbrier and the Trough Creek and the Loyalhanna limestones, which are far from the area I was discussing, I am sure he will pardon me if I retaliate by pointing out (his page 271) that *Syringothyris* is known at several places in the Devonian of the Appalachian region, the lowest such occurrence being near Jefferson, Ohio, and that (his page 268) *Archaeopteris* is well-known all down through the sub-Chemung beds even into the Hamilton (reds). The difficulty here is that in using the expression "beds so low as the Portage," Doctor White is talking what is to-day a dead language to Devonian stratigraphists, for type Portage is type Chemung (chronologically) and type Catskill is Hamilton. The frail pinnules of this

---

[8] Bradford Willard, "Catskill" Sedimentation in Pennsylvania, Bull. G. S. A., 44, 500, 1933. Willard has slipped in saying that I mentioned Blossburg in this connection, but I did transmit to him Mr. Butts's suggestion (loc. cit., 1908, 198) that the fossiliferous beds were Conewango (Venango). All of us were wrong. (See footnote 6.)

[9] Unfortunately, Doctor White has quoted (and accurately) two paragraphs that, with their grammatical errors, do not stand in type as I wrote and wished them.

"fern" could not survive flotation to the distant depths where the "Portage" facies was depositing, but they are plentiful enough in the synchronous continental strata to eastward.

CONCLUSION.

From what has been recounted I believe it must be clear that the old lines of reasoning with regard to these delta deposits may no longer claim dependability. Because some one section through them is "very much like" another such section many miles away, age identity therewith cannot be safely assumed but must still be patiently proved by more precise criteria. The very fact that the Chemung fossils present beneath the continental strata of the Broadtop field are admittedly absent beneath the seemingly corresponding strata at Mauch Chunk is of itself a red flag calling for utmost caution. One wonders, then, on what evidence Doctor White confidently locates this missing Chemung in "the median part" of the 7,000 feet of "Catskill" red-beds there; though I am almost in agreement with him on that score. But where then are the Canadaway, Conneaut and Conewango?

It is interesting in this connection to turn once more to Lesley, to whom Doctor White appeals, and read (pages 1577, 1641) concerning the "Catskill," "Pocono" and "Mauch Chunk" that it is impossible for geologists to agree or fix upon any planes of division (I am practically quoting him) between them. But this is in itself a challenge to all subsequent workers. Whatever the mistakes and shortcomings of my own efforts in this direction they have at least had the merit of bringing out from Doctor White a new body of evidence and information that might otherwise have passed into oblivion. Whether he agrees with me or not in his conclusions, I should like to see much more extended publication of the wealth of experience of this our master botanist of the Paleozoic.*

CATSKILL.
APRIL 16, 1934.

---

*Since this paper was submitted I have learned of the work of Norman Spenser Wagner in the Pocono plateau. His map and thesis fully confirm I. C. White's discovery that the "Pocono" does not exist on that plateau.

STRUCTURAL DETAIL NEAR THE WESTERN BORDER OF THE THRUST SHEETS NORTH OF SHOSHONE RIVER, WYOMING.

MARTIN M. SHEETS.

The Problem of the Heart Mountain Thrust.

Along the Shoshone River west of Cody, Wyoming, a group of limestone masses lie thrust upon the truncated edges of Cretaceous and Early Tertiary formations. Heart Mountain and McCulloch Peaks represent their easternmost outposts.[1] The distance from these to the westernmost exposures of the thrust masses measures over 28 miles. This is overthrusting on a scale entirely out of harmony with the structure of the relatively simple, broad mountain uplifts in the midst of which it lies, such as the Beartooth, Bighorn, Owl Creek, and Wind River Mountains. On the west side, the thick volcanics of the Absarokas occupy the place where the roots of the overthrust must be sought.

The extraordinary character of this group of thrust masses was soon recognized as one of the major problems of the Beartooth-Bighorn region, when that region was made the object of a project of coöperative research.[2]

At first, the Heart Mountain thrust had been thought to be intimately connected with the thrust plane at the east foot of the Beartooth Mountains, perhaps its extension south and southwestward. This view was expressed, e.g.; in Guidebook 24 of the 16th International Geological Congress, 1933.[3] It had to be abandoned, when detailed mapping showed that the Beartooth thrust plane dies out southward, the mountain ending as a simple plunging anticline.[4]

Further analysis of the problem led to the suspicion that a closer connection may exist between the volcanic phenomena of the Absarokas and the thrust masses to the east of them.[5]

In the summer of 1933, the detailed mapping of the two largest of the thrust masses was begun under the auspices of the Geological Society of America as part of the Beartooth-Bighorn project. The large limestone mass which may be named the Logan thrust sheet after a conspicuous point on its south front, was mapped by R. A. Laurence and the writer with the assistance of Walter E. Dietrich, on the scale of 1 : 30,000. The map together with a detailed account, including petrographic studies, is to be published later.

---

[1] Dake, C. L.: "The Hart Mountain overthrust and associated structures in Park County, Wyoming." Jour. Geol., vol. 26, pp. 45-55, 1918. Hewett, D. F.: "The Heart Mountain Overthrust, Wyoming," Jour. Geol., vol. 28, pp. 536-557, 1930.

[2] Bucher, W. H., Thom, Jr., W. T., and Chamberlin, R. T.: "Geologic problems of the Beartooth-Bighorn Region." Bull. Geol. Soc. America, vol. 45, pp. 167-188, esp. pp. 176-177, 1934.

[3] Internat. Geol. Congr., 16 Session, 1933, Guidebook 24, Washington, p. 3 and pl. 3, 1932.

[4] Hughes, R. V.: "Geology of the Beartooth Mountain front in Park Co., Wyoming." Proc. Nat. Acad. Sci., vol. 19, pp. 239-253, 1933.

[5] Bucher, W. H.: "Volcanic explosions and overthrusts," Transactions of the American Geophysical Union, 14th Ann. Meeting, pp. 238-242, 1933.

The most characteristic feature of the thrust sheet was found to be its far-reaching fragmentation by minor faults. The writer decided to map a typical part of the thrust mass on a scale sufficiently large to bring out these details of structure. The west side of Trout Creek Valley, about four miles north of the North Fork of Shoshone River in Park County, Wyoming, was selected for this purpose. It was mapped on the scale of 1 : 6000,[6] the map being here reproduced with considerable reduction.

The following pages are devoted to a description of significant structural features and an attempt at an interpretation.

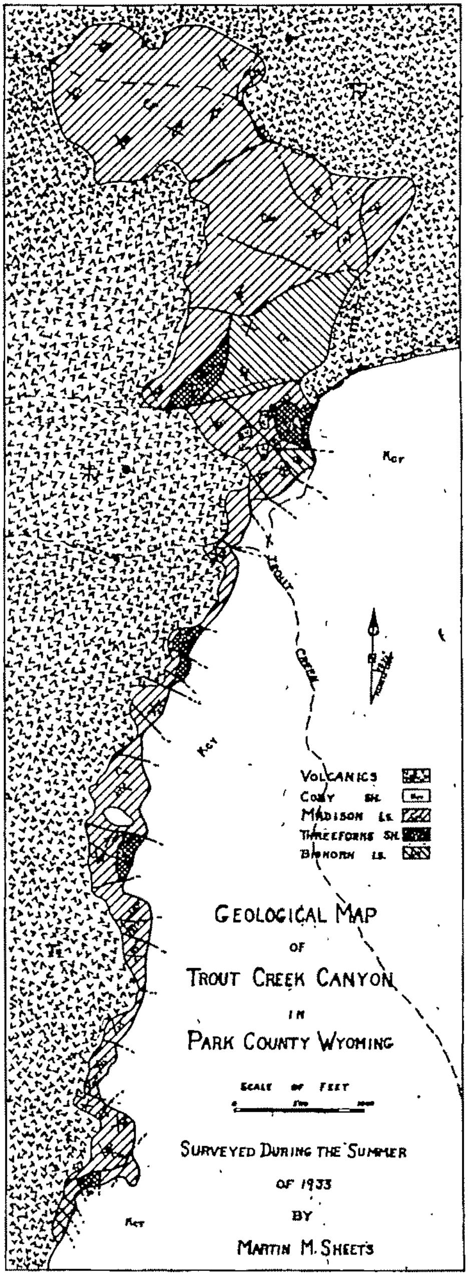
The Geologic Column.

In the region shown on the map the geologic column includes five units ranging in age from Ordovician to Tertiary, as follows:

Volcanics (Tertiary)
  1200 feet of basic explosive and flow breccia containing in other places a series of basic flows.
Unconformity
Cody (Cretaceous)
  Fine-grained gray, dark brown and black shale, about 1000 feet exposed. Of Colorado age.
Unconformity
Madison (Mississippian)
  Thin to heavy bedded massive limestone, approximately 900 feet thick, not entirely exposed.
Threeforks (Devonian)
  Well indurated, fissile shale, ranging in color from red through blue to black and containing thin layers of sandstone and streaks of carbonaceous material. One hundred feet in thickness.
Erosional Unconformity (?)
Bighorn (Ordovician)
  Moderate to heavy bedded massive limestone, containing thick, white porcelainous layers. Three hundred feet exposed.

---

[6] The writer wishes to express his thanks to R. A. Laurence and Walter E. Dietrich for valuable assistance in this work.

Kcy
Trout Creek
Kcy
Volcanics
Cody Sh.
Madison Ls.
Threeforks Sh.
Bighorn Ls.
Geological Map
of
Trout Creek Canyon
in
Park County Wyoming
Scale of Feet
0
500
1000
Surveyed During the Summer
of 1933
by
Martin M. Sheets
Kcy

The Paleozoic limestones and less plentiful shales form cliffs which rise above slopes underlain by the Cody formation. The limestones are, in turn, surmounted by greater cliffs of Tertiary volcanic breccia. In no place could the actual contact of Paleozoic strata on Cody be located, but their persistent position above the Cretaceous shales is accepted as conclusive evidence of the thrust relation.

Structural Detail.

The Trout Creek Canyon district embraces an area of very complicated small-scale structures superimposed on one major thrust which placed Paleozoic sediments on top of the Cretaceous shales of the Cody formation. The younger disturbances took the form of: 1. High-angle strike-slip and normal and reverse dip-slip faults, many of them combined with some hinging movement. 2. Low-angle thrusts. 3. Asymmetrical open folds, locally overturned.

One very interesting locality is that marked by a small outcrop of Threeforks shale in the southwest corner of the map. The cliff at this point is about 300 feet high and is capped by volcanics which overlie a section of Madison limestone. The contact of these two is peculiarly irregular and indicates that the volcanics have been thrust several feet over the surface of the limestone, probably from the west. The block of Devonian shale, which occupies the lower center of the cliff, dips steeply northward and is cut off at both ends by high-angle faults which dip steeply toward the west. Only the westernmost fault is clearly distinguishable. It strikes about N. 20°, W. and slickensides on its surface indicate relative movement of the most westerly block south and down at an angle of about 15 degrees. The fact that the Threeforks-Madison contact stands at least 150 feet higher in the central block in consequence of this nearly strike-slip fault indicates that the net displacement must have figured in several hundreds of feet in a nearly north-south line.

The east end of this same cliff is shattered by numerous faults most of which dip west, the direction of movement being indeterminate. Seemingly beneath this east portion of the cliff lies a small block of questionable Madison with bedding vertical and a little overturned toward the west. Another limestone block beneath that which stands vertical appears to have horizontal bedding, but of that one cannot be certain.

This one exposure serves as an excellent example of the general complexity of the Trout Creek structure.

Following the cliff line north from this point one may observe a series of limestone blocks, which show no sign of internal contortions, dipping in all directions and at all angles. The contacts between these blocks are usually obscured by talus either from the limestones themselves or from the towering volcanic cliffs above. However, in two places high-angle faults are visible and this fact, backed by the knowledge that the section varies widely from one block to the next, led the author to conclude that similar faults mark all of the contacts. The diversity of dips indicates that many of these breaks are of the hinge type and a highly complicated system of localized forces must be postulated to explain them. This will be discussed more fully below.

In Trout Creek Canyon proper, where the string of Paleozoic outcrops meets the creek in the northern part of the map, the system of high-angle faults is made more complex by asymmetrical folding in three directions.

The first such structure is that which exposes Threeforks at creek level surrounded by Madison on three sides and overturned on the northeast corner. This requires local forces acting from the southwest.

Immediately north of this structure and separated from it by a fault is a considerably larger block in which are exposed portions of all three Paleozoic formations, Bighorn in the east, Threeforks partly cut off by a secondary cross fault in the middle, and Madison in the west portion. All three formations dip west and the angle increases progressively in that direction. An orthodox interpretation of this structure calls for forces acting from the east, and the back slope of this arch, if one ever existed, extended to the east into what is now an area of volcanics, which must have been removed in prevolcanic time.

Adjoining the last described feature on the north lies a mosaic of blocks of Madison in which dips vary widely in angle and direction. Beyond them is found the most complete structure in the area. It is bisected by the main fork of Trout Creek and is exposed as an asymmetrical arch steepened toward the northeast, indicating forces from the southwest.

Interpretation.

It is plain from the above description that the history of this region must have involved local forces acting from the north, east, southwest, and probably many other directions.

It is deemed highly improbable by the author that these small-scale contortions were produced before the Heart Mountain Thrust, first because any block so highly contorted could hardly have withstood such great thrusting forces without shearing along many nearly horizontal planes, and second because the elevation of the Paleozoic-Cretaceous contact changes far too abruptly and too much to represent the bottom of any thrust block. It must have been contorted since the major thrust was formed.

Both of the above statements oppose the idea of the minor structures being contemporaneous with the major feature, as does the fact that they are due to forces acting from so many different directions. The lack of any indication of schistosity or cleavage in the individual blocks and the complexity of direction of movement both disfavor any normal tectonic hypothesis. The presence to the west of great thicknesses of eruptive rocks suggests a connection between the intensely disturbed structure and the volcanism of the region.

The eruptive rocks in this area belong to four types. 1. A water-deposited agglomerate; 2, a mud flow breccia; 3, dry ash and bomb accumulations; and 4, an originally semi-liquid flow-breccia. The last two types are by far the most abundant.

Many of the boulders in the dry accumulations are fractured along numerous nearly vertical planes. As no similar fractures occur in the associated matrix it seems logical to suppose that these breaks were the result of compaction of the thick mass while the matrix was still plastic. This suggests quite rapid accumulation.

The initial dips in these thick deposits change direction and angle very suddenly and in very short distances, indicating that they came from numerous closely spaced sources. This idea is corroborated by the number of intermittent dikes and sills which forced their way into the explosives from every conceivable direction.

In short, the extrusion of these volcanics must have been accompanied by considerable violence of the short-lived, multidirectional type, ideally suited to producing the structures noted in the Paleozoic sedimentary rocks with which they are intimately related. These disrupting forces acted on a limestone thrust sheet which had been greatly thinned and weakened if not actually cut in two by erosion in pre-volcanic time.

It should be noted that there are many places outside of Trout Creek Canyon where the thrust sheet is similarly badly contorted and that invariably these areas are associated with centers of great volcanic activity.

In view of the above determinations it is the opinion of the author that the small-scale structures in the Trout Creek Canyon Area certainly post-date the major thrust, and that they are the result of the forces set up by the extrusion of the volcanics which surround them.

University of Cincinnati,
Cincinnati, Ohio.

THE SYSTEM, $MgO-FeO-SiO_2$.

N. L. BOWEN AND J. F. SCHAIRER.

INTRODUCTION.

In view of the great importance of ferromagnesian silicates as rock-forming minerals a study of equilibrium in the system, $MgO-FeO-SiO_2$, may be expected to reveal facts and relations of much value in deducing the conditions of formation of many rocks. With these considerations in mind investigation of the system was undertaken. The procedure adopted and the results attained are here presented.

FUNDAMENTAL SYSTEMS.

Of the three fundamental systems two had already been made the subject of detailed studies. These are the system, $MgO-SiO_2$,[1] and the system, $FeO-SiO_2$.[2] The equilibrium diagrams are here reproduced in Figs. 1 and 2, respectively. The third fundamental system, MgO-FeO, has not been investigated in detail. It has, in itself, no great petrologic importance. The one end member, FeO, melts incongruently with separation of metallic iron and formation of a liquid containing oxygen in excess of the ferrous ratio, and this fact so complicates the detailed relations, that for their full elucidation a greater amount of investigation would be required than is warranted for our present purposes. Nevertheless, the broader relations are sufficiently clear. We have ascertained that MgO and FeO form a complete series of solid solutions, which we here term magnesio-wüstites. We find also that the temperature of melting rises rapidly as MgO is added to FeO, soon reaching a value above the melting point of iron and thus precluding further investigation by the method here followed. If the incongruent character of melting, with consequent complications, is neglected, the form of equilibrium diagram indicated by these facts is given in Fig. 3.

---

[1] Bowen, N. L., and Andersen, Olaf: This Journal, 37, 487-500, 1914. Greig, J. W.: This Journal, 13, 15, 1927.

[2] Bowen, N. L., and Schairer, J. F.: This Journal, 24, 177-213, 1932.

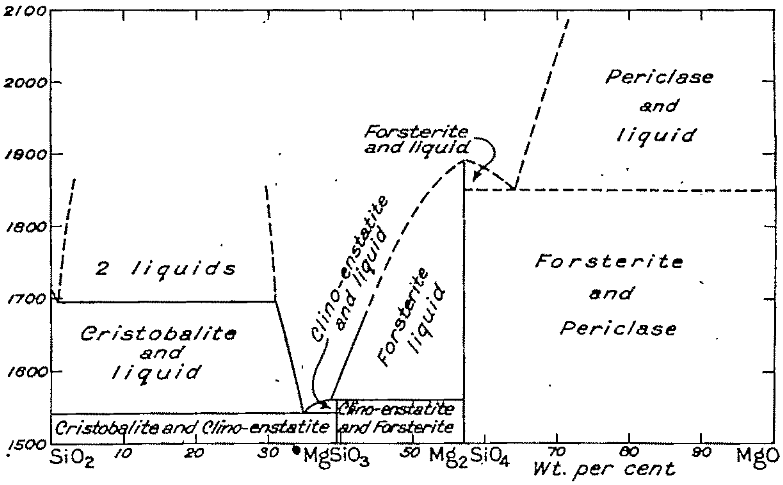


Fig. 1. Equilibrium diagram of the system, $MgO-SiO_2$.

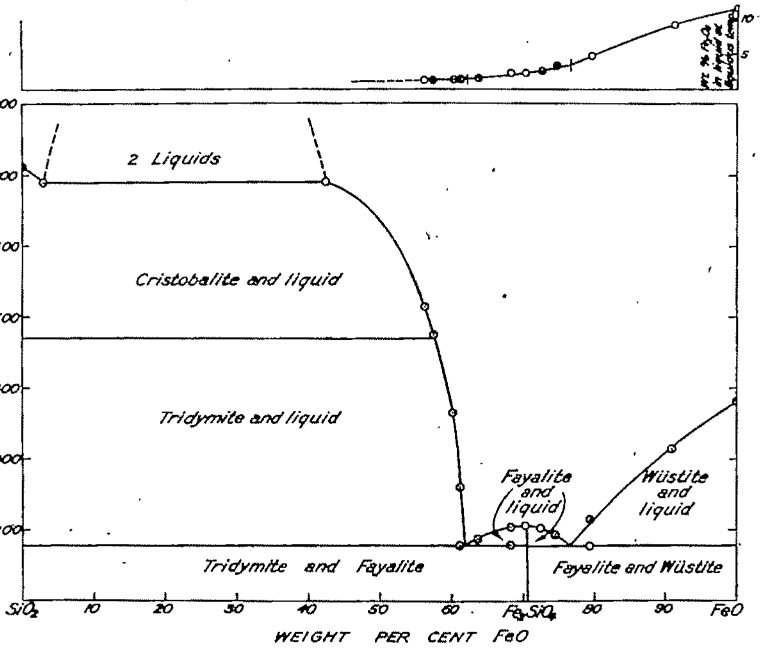


Fig. 2. Equilibrium diagram of the system, $FeO-SiO_2$.

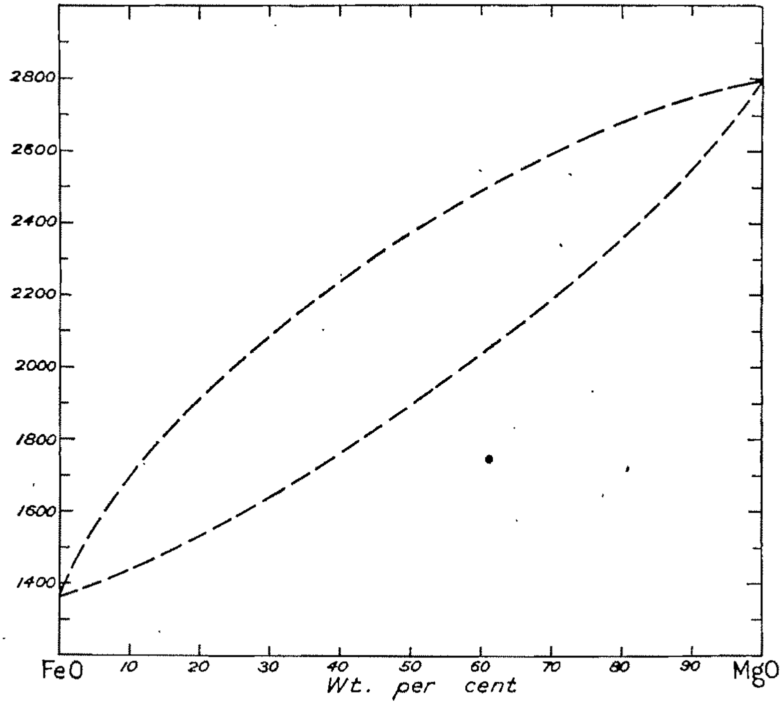


Fig. 3. General form of equilibrium diagram of the system, MgO-FeO.

METHOD OF INVESTIGATION.

Preparation of Mixtures and Thermal Study.

The methods used for the investigation of mixtures containing iron in the ferrous state have been described in detail in the paper on the system, FeO-SiO_2, already referred to.[8] Briefly, it may be said that mixtures were prepared by taking silica, ferrous oxalate (or Fe_2O_3) and MgO in the proportions calculated to give the desired product, and melting them together three times in a platinum crucible in a Meker furnace. Thus was obtained a product deviating somewhat from the desired product by reason of a small deficiency of iron (removed by the Pt crucible) and also the existence of a little of the iron in the ferric state. Small samples of the mixture were then

[8] Bowen, N. L., and Schairer, J. F.: This Journal, 24, 178-186, 1932.

heated in iron crucibles in a stream of nitrogen and the temperatures of beginning of melting, of completion of melting, and of any other changes of phase were determined by the method of quenching, combined with microscopic determination of the phases in the quenched product. Upon heating in the iron crucible, a small change of composition of the charge occurs which is principally due to reduction of ferric oxide by the iron crucible and consequent increase of the total iron content of the charge. This increase may partly balance, or it may more than balance, the deficiency produced by melting in platinum. In all cases it was, therefore, necessary to make a chemical analysis of each mixture after a run in an iron crucible at the temperature at which a change of phase was found to occur. Ordinarily, the temperature of the run made for this purpose was that at which completion of melting took place and the analysis thus gave the composition of the liquid at the liquidus point for the particular mixture. By repeating this procedure for a series of mixtures and plotting the determined liquidus temperatures and analyzed compositions (with microscopic determination of the crystal phases) the liquidus surfaces can be constructed. In a similar manner the solidus relations may be determined.

The readings of the thermocouples used to measure temperatures were checked by frequent calibration at standard melting points defined as follows: NaCl 800.4, Au 1062.6, Li_2SiO_3 1201, $CaMgSi_2O_6$ 1391.5, and Pd 1549.5.

Methods of Chemical Analysis.

The methods used in determining ferrous and ferric oxides have been described in detail in a former paper.[4] The relative proportions of MgO and SiO_2 are, of course, fixed by synthesis and require no analytical determination.

EXPERIMENTAL RESULTS.

The results of the determination of the temperatures of the phase changes by the method of quenching, together with the analyses of the mixtures, are given in Table I. It will be noted that, even after holding the mixtures in a molten state in an iron crucible in nitrogen, some of the iron remains in the

---

[4] Bowen, N. L., Schairer, J. F., and Posnjak, E.: This Journal, 26, 197, 1933.

TABLE I.

(a) Mixtures Closely Approximating the Metasilicate Join.

Composition of liquid at liquidus temperature				Temp. of completion of melting ± 4°	Primary phase	Temp. of beginning of melting ± 8°	Refractive index of glass	Composition reduced to	
FeO	Fe_2O_3	MgO	SiO_2					$MgSiO_3$	$FeSiO_3$
17.53	0.26	27.63	54.58	1495	clino-pyroxene	1415	1.616	..*	..*
21.15	0.28	24.21	54.36	1465	clino-pyroxene	1375	1.621	60	40
27.84	0.66	19.72	51.78	1427	clino-pyroxene	1340	....	..*	..*
30.10	0.45	17.86	51.59	1416	clino-pyroxene	....	....	45	55
32.38	0.48	16.03	51.11	1400	tridymite and clino-pyroxene	1305	1.648	40	60
38.43	0.59	11.88	49.10	1420	tridymite	....	....	..*	..*
44.22	0.89	7.81	47.08	1460	tridymite	....	....	..*	..*
49.23	1.22	3.89	45.66	1500	cristobalite	....	....	..*	..*

* These mixtures deviate slightly from metasilicate compositions. They nevertheless serve to fix the position of isotherms at points very close to the metasilicate join.

TABLE I—*Continued.*

(b) Mixtures Closely Approximating the Orthosilicate Join. Primary Phase Olivine.

Liquidus Determinations

Composition of liquid at liquidus temperature				Temperature of completion of melting ± 4°	Composition reduced to	
FeO	Fe_2O_3	MgO	SiO_2		Mg_2SiO_4	Fe_2SiO_4
61.89	1.65	5.72	30.74	1340	10	90
56.10	1.46	11.08	31.36	1450	20	80
50.66	1.58	14.53	33.23	1495	25	75

Solidus Determinations

Approximate bulk composition of mixture		Temperature ± 4°	Composition of solid phase determined optically	
Mg_2SiO_4	Fe_2SiO_4		Mg_2SiO_4	Fe_2SiO_4
10	90	1275	20	80
10	90	1317	30	70
25	75	1410	46	54
25	75	1440	52.5	47.5
25	75	1465	55	45
40	60	1495	59	41

TABLE I—*Continued.*

(c) Mixtures Having Olivine as the Primary Phase. See also Table I(b).

Composition				Temperature of completion of melting ± 4°	Refractive index of glass ± .003
FeO	Fe_2O_3	MgO	SiO_2		
58.64	1.77	4.95	34.64	1305	....
57.73	1.38	3.07	37.82	1242	1.750
54.16	1.25	4.95	39.64	1268	....
52.59	0.95	5.66	41.80	1275	1.725
50.25	1.13	9.72	38.90	1345	1.730
53.66	1.06	8.05	37.23	1335	....
49.33	1.16	12.88	36.63	1430	....
46.18	0.93	9.40	43.29	1315	1.702
44.80	1.11	10.80	43.29	1350	1.700
44.72	0.76	8.92	45.60	1305	....
39.05	1.04	14.98	44.93	1400	1.687
44.30	1.25	14.85	39.60	1435	1.716
43.01	1.07	18.30	37.62	1509	....
39.88	0.77	19.78	39.57	1509	....
34.90	0.79	19.78	44.53	1470	....
37.30	0.61	14.55	47.54	1380	1.668
30.66	0.79	21.55	47.00	1470	1.661
26.47	0.58	22.40	51.55	1463	....
26.51	0.58	24.30	48.61	1485	1.648
19.02	0.35	26.88	53.75	1485	....

TABLE I—*Concluded.*

(d) Mixtures Having Clino-pyroxene as Primary Phase. See also Table I(a).

Composition				Temperature of completion of melting ± 4°	Refractive index of glass ± .003
FeO	Fe_2O_3	MgO	SiO_2		
19.21	0.51	24.80	55.48	1475	....
26.44	0.59	19.45	53.52	1430	1.633
28.35	0.69	19.30	51.66	1424	1.642
40.05	0.63	11.87	47.45	1352	1.672
(e) Mixtures Having Tridymite as Primary Phase. See also Table I(a).					
51.36	0.89	4.78	42.97	1370	1.713
(f) Mixtures Having Cristobalite as Primary Phase. See also Table I(a).					
15.61	0.37	25.70	58.32	1495	....
29.83	0.59	15.91	53.67	1505	1.638

ferric state. In the former papers it was shown that even after melting in an iron crucible in an evacuated, sealed, silica-glass tube, there is still persistence of some ferric iron in the silicate liquids, and reasons were there given for the belief that the small amount of ferric iron persisting in the nitrogen runs represents equilibrium with metallic iron. The same condition must be regarded as obtaining in the present mixtures as well. Iron is incapable of further reducing the Fe_2O_3 content of these silicate melts. An attempt at reduction with the aid of a reducing agent would result only in the separation of metallic iron from the liquid without decrease of its Fe_2O_3 content.[6]

The manner in which the equilibrium content of Fe_2O_3 varies with the composition of the liquid is shown in Fig. 4. The amount of Fe_2O_3 is not proportional to the total iron but it is much more nearly so than in the system, CaO-FeO-SiO_2.[5]

There is always some iron in the ferric state in the liquid which is in equilibrium with the various crystalline ferrous silicates of the system and with iron. It follows that these silicates must melt incongruently with separation of iron. This behavior has been demonstrated for the compound fayalite in the former papers.

For a full and accurate presentation of the experimental results it would, in the light of the above facts, be necessary to refer them to quaternary equilibrium in the system, MgO-Fe-Fe_2O_3-SiO_2. This would require the use of a tetrahedron for the graphic presentation. The results are much more conveniently and lucidly presented by neglecting the small amounts of Fe_2O_3 in the liquid, calculating the total iron as FeO and plotting the data on a ternary diagram. In the following this course has been adopted, but we must emphasize that the liquids always contain a little ferric iron, the approximate amount of which can be ascertained for any liquid by reference to Fig. 4. It is not possible for us to remind the reader repeatedly of this fact. Throughout the paper, whenever we speak of a binary or a ternary system (or a binary or ternary invariant point) it is to be borne in mind that the system (or point) can be treated as binary or ternary respectively only when the small content of Fe_2O_3 is arbitrarily regarded as FeO.

---

[6] Cf. this Journal, **26**, p. 203, Fig. 4, 1933.

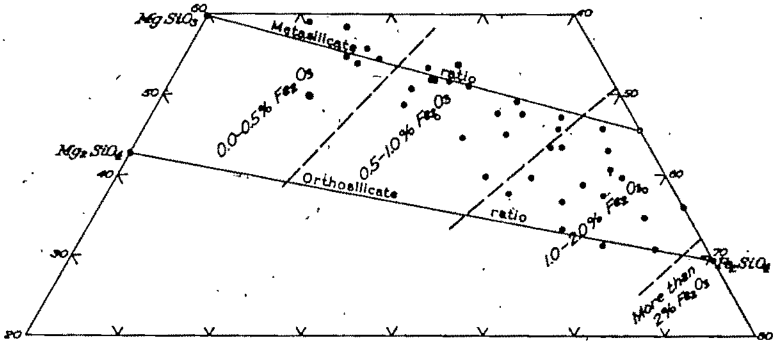


Fig. 4. Diagram showing the approximate Fe_2O_3 content of liquid mixtures of MgO, SiO_2 and Fe oxide, in equilibrium with metallic iron. The position of the figure in the general triangle is readily made out by comparison with Fig. 5.

EQUILIBRIUM DIAGRAMS.

In Fig. 5, based on the results given in Table I, are shown the fields in which each of the solid phases encountered in the system occurs as the primary phase in equilibrium with liquid. Fig. 6 gives the same information together with isotherms showing the temperature of complete melting (solution) of the primary phase for the various compositions, in other words, the temperatures of points on the liquidus surfaces. Although Figs. 5 and 6 are largely self-explanatory, a few comments

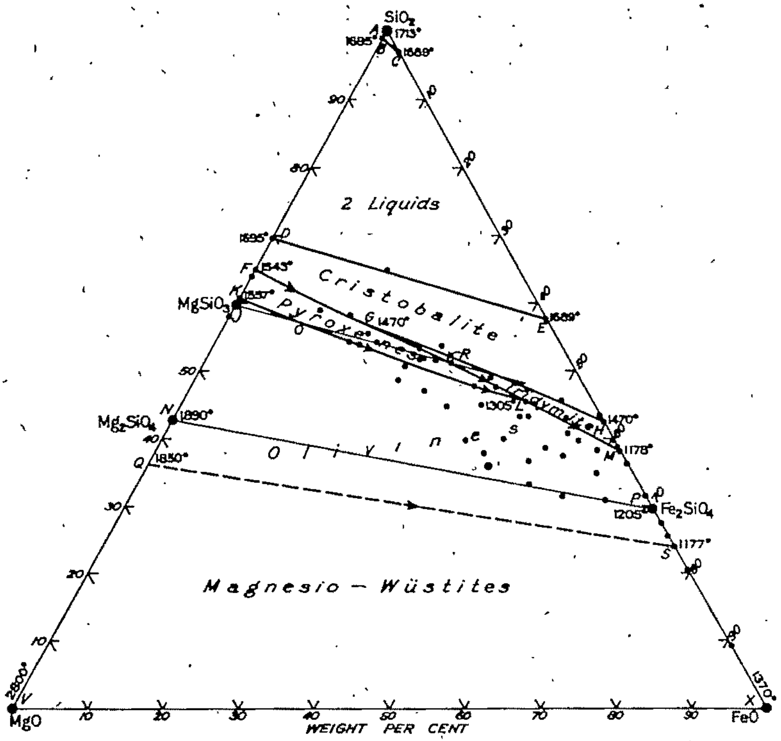


Fig. 5. Equilibrium diagram of the system, MgO-FeO-SiO_2, showing the fields of stability of crystalline phases in contact with liquid. (Small amount of Fe_2O_3 in all liquids; see Fig. 4 and Table I).

The Various Fields and Their Boundary Curves.

The field of any crystalline phase in Fig. 5 is, of course, the projection of its liquidus surface upon the triangular base of the solid T-X (temperature-composition) model. The field of cristobalite is, therefore, in two parts, *ABC* and *DFGHE*, corresponding with the division of the cristobalite liquidus surface into two parts separated by an area in which no liquidus surface exists.[6] This is the area *BCED* (marked two liquids) the boundaries of which have been determined by Greig and the curves *BC* and *DE* are taken from his work.[7] Our investigation was confined to temperatures below 1520° on account of the limitation imposed by the melting point of our iron crucibles.

---

[6] The liquidus surface of any crystalline phase may be defined as that T-X surface which is the locus of all points each of which represents simultaneously the composition of a liquid and the temperature at which that liquid is in equilibrium with said crystalline phase. Since no liquid of composition represented by a point within the area *BCED* can exist at temperatures where cristobalite (or any other crystalline phase) can co-exist with it, the area *BCED* is properly regarded as an area in which there is no liquidus surface.

By reason of the ready mutual replacement of Mg and Fe″ in their silicate compounds and the failure of double salts, the number of fields and field boundaries in the system is reduced to a minimum. For the same reason there is no ternary eutectic in the system; the low points lie on the FeO-SiO_2 side of the triangle and all fusion surfaces slope towards that side. This makes for great simplicity of the fusion surfaces. The one notable complication of the liquidus relations is the fact that the field of the metasilicates or monoclinic pyroxenes *FLK*

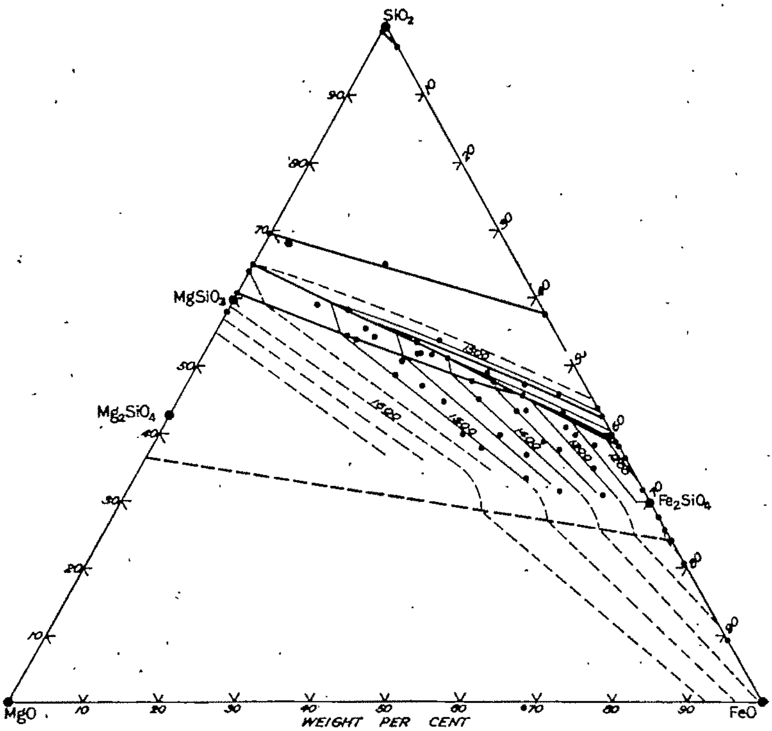


Fig. 6. Same as Fig. 5 with isotherms added.

---

[7] Greig, J. W.: This Journal, 13, 144, 1927.

(Fig. 5) is wedge-shaped and vanishes to a point at *L*. Beyond this point no metasilicate field is interposed between the orthosilicate (olivine) field and the silica (tridymite) field. Some such relation was, of course, to be expected since the compound $FeSiO_3$ does not exist, although solid solutions containing nearly 90 per cent of that molecule can form. It is of interest that of these metasilicate solid solutions (pyroxenes) the more magnesian (*J* to *O*) lie in the olivine field. Those of intermediate composition (*O* to *R*) lie in the pyroxene field whereas those rich in iron (from *R* onward) lie in the field of silica in one form or another. The one end of the series thus melts incongruently with separation of olivine, a less siliceous phase, whereas the other end of the series melts incongruently in what we may term the opposite direction, that is, with the separation of a more siliceous phase, indeed silica itself. This change of character of the incongruent melting in a single solid solution series has not been observed in any system nor has it been discussed theoretically. The details of the relations involved will be brought out later with the aid of a diagram representing a section along the metasilicate join.

The boundary curve *QS* between the fields of olivine and of magnesio-wüstite is only roughly located except at *S* and is therefore shown as a broken line. Of the olivines the complete series *N-P* lies in the olivine field.

Invariant Points.

The invariant points are listed in Table II. The only ternary invariant point on the liquidus surface, other than the inversion point *G*, is the point *L* at which tridymite, monoclinic pyroxene, and olivine are in equilibrium with liquid of composition *L* at 1305°. The exact composition of the several phases is given in Table II. As already indicated, the point *L* is not eutectic, the reaction being liquid + pyroxene $\rightleftarrows$ olivine + silica.

The Binary System, Mg_2SiO_4-Fe_2SiO_4.

There is only one join in the ternary system that constitutes a binary system. This is the orthosilicate join, the crystalline end members being the familiar rock-forming minerals forsterite and fayalite. The relations in this system are very simple. A complete series of solid solutions of type I (Roozeboom) is formed. The equilibrium diagram is given in Fig. 7.

TABLE II.

Invariant Points.

Letter (Fig. 5)	Temp. °C	Phases
		Unary
A	1713 ± 5	Cristobalite and liquid SiO_2 (Greig)
N	1890 ± 20	Forsterite and liquid Mg_2SiO_4
P	1205 ± 3	Fayalite and liquid Fe_2SiO_4
V	2800	Periclase and liquid MgO (Kanolt)
		Binary
B	1695 ± 5	Cristobalite, liquid B (MgO 0.8 SiO_2 99.2) and liquid D (MgO 31 SiO_2 69) (Greig)
D	1695 ± 5	same as B (Greig)
C	1689 ± 15	Cristobalite, liquid C (FeO 3 SiO_2 97) and liquid E (FeO 42 SiO_2 58) (Greig)
E	1689 ± 15	same as C (Greig)
F	1543 ± 2	Cristobalite, clino-enstatite and liquid F (MgO 35 SiO_2 65)
K	1557 ± 2	Forsterite, clino-enstatite and liquid K (MgO 39 SiO_2 61)
H	1470 ± 10	Cristobalite, tridymite and liquid H (FeO 57.5 SiO_2 42.5)
M	1178 ± 2	Tridymite, fayalite and liquid M (FeO 62 SiO_2 38)
Q	1850 ± 20	Forsterite, periclase and liquid Q (MgO 64 SiO_2 36)
S	1177 ± 5	Fayalite, wüstite and liquid S (FeO 76 SiO_2 24)
		Ternary
G	1470 ± 10	Cristobalite, tridymite, clino-pyroxene ($MgSiO_3$ 86 $FeSiO_3$ 14) and liquid G (MgO 23.5 FeO 20 SiO_2 56.5)
L	1305 ± 5	Tridymite, clino-pyroxene ($MgSiO_3$ 38 $FeSiO_3$ 62), olivine (Mg_2SiO_4 32 Fe_2SiO_4 68) and liquid L (MgO 9 FeO 46 SiO_2 45)

The curves are determined only up to 1500°, below which temperature they are shown as full lines. Above this temperature they are produced to meet at the melting point of forsterite, 1890°, and are shown as broken lines. The liquidus is determined by the usual method of finding the temperature of final disappearance of crystals and is very accurately placed. The materials do not lend themselves to determining the solidus by finding the temperature of beginning of melting because it is impossible to get them in a perfectly homogeneous condition, i.e., free from zoning. The solidus was therefore determined by holding a mixture at a measured temperature at which it consisted of liquid and crystals, and then quenching. The product of such procedure consists of homogeneous, euhedral crystals of olivine (the primary phase) embedded in a feathery aggregate of olivine formed by rapid crystallization. By determining the optical properties of the euhedral crystals the composition of the solid phase and therefore the position of the solidus for the temperature of the run was fixed. The accuracy is not as great as that attained in the fixing of points on the liquidus. The error may probably be as much as 3 to 4 in the percentage of forsterite and fayalite in the crystals.

The determinations upon which the position of solidus and liquidus is based are given in Table I.

A diagram of the type thus determined for the olivines is so familiar to petrologists in the plagioclase diagram that no special discussion of it need be given.

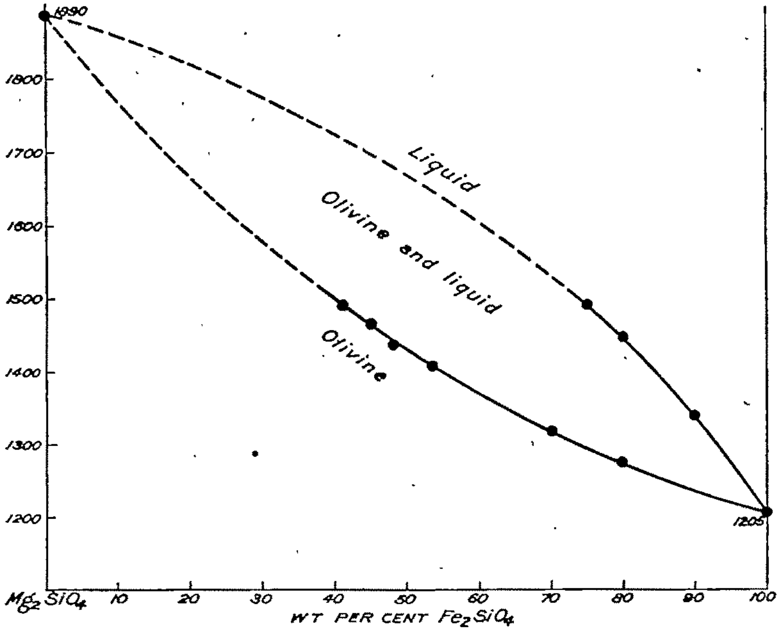


Fig. 7. Equilibrium diagram of the system, Mg_2SiO_4-Fe_2SiO_4.

The Metasilicate Join.

Although the metasilicate join does not represent a binary system, nevertheless many of the relations of metasilicate compositions are best brought out with the aid of a section along this join. The resultant diagram is given in Fig. 8, where the curves that refer to binary equilibrium are shown in heavy lines, and those referring to ternary equilibrium in lighter lines. These lighter lines, therefore, give only the temperature at which phase changes occur in a mixture of a given total composition. They do not give the composition of all the phases concerned in the equilibrium, since these relations can be shown only with the aid of a ternary diagram. It will be noted that only the curves *BS* and *OR* with *BO* and *SR* and the curves *KY* and *KX* indicate binary equilibrium. All other relations depicted are ternary.

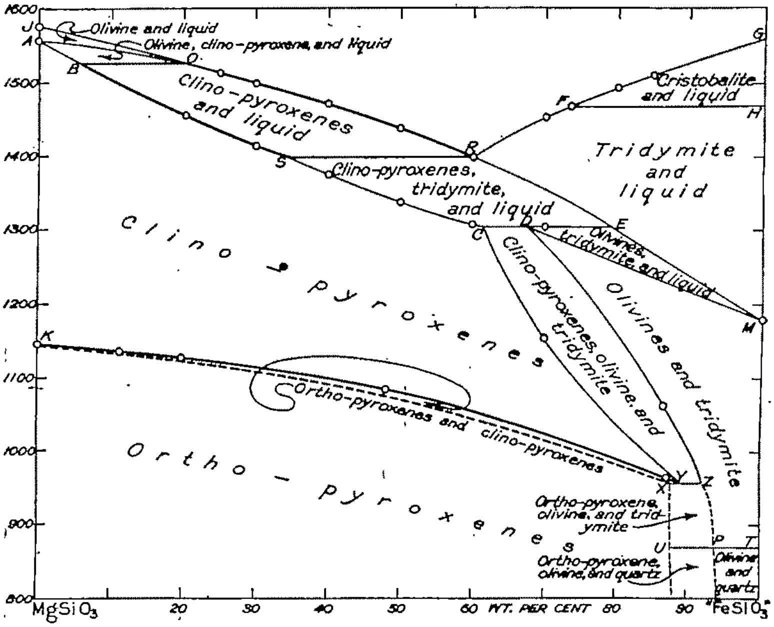


Fig. 8. Equilibrium diagram of mixtures of metasilicate ratio. Heavy curves refer to binary equilibrium and light curves to ternary equilibrium. (Binary and ternary respectively only when small amounts of Fe_3O_4 present in liquids are treated as FeO, see Fig. 4.)

The Relation between Orthorhombic and Monoclinic Metasilicates of Fe″ and Mg.

At low temperatures all metasilicate mixtures containing up to nearly 90 per cent $FeSiO_3$ exist, at equilibrium, as orthorhombic pyroxenes, corresponding with the natural enstatite-hypersthene series. At higher temperatures the same mixtures exist, at equilibrium, as monoclinic pyroxenes, corresponding with the less well known clino-enstatite, clino-hypersthene series. Members of the two series bear an enantiotropic relation to each other. The inversion temperature, which is at 1140° at the $MgSiO_3$ end of the series, falls off with increase of $FeSiO_3$ as shown by the curve KY, and at the extreme iron-rich member it lies at 955° approximately.

This conclusion is somewhat at variance with that reached by earlier investigators, but appears to be the only one justified by the facts now available. In the earlier work, which was confined to the magnesian end-member, it was found that enstatite could be transformed at high temperatures to clino-enstatite but the reverse change was not accomplished, and for that reason the inversion was regarded as irreversible and enstatite as a monotropic form.[8]

In the present study we used natural pyroxenes in part and also synthetic materials. We have found it impossible to induce any synthetic metasilicate mixture of the system to crystallize completely in the orthorhombic form. When glass is devitrified at low temperatures a fibrous product is obtained which, in the case of the magnesian member, was regarded as orthorhombic by the earlier investigators. Though this conclusion seemed then to be justified, examination by X-rays of material so prepared, including some made by the earlier investigators, shows that the powder pattern does not correspond with that of enstatite.[9] Such preparations cannot, therefore, serve as a starting point for a study of the transformation from orthorhombic to monoclinic pyroxene, even although it is true that by heating this fibrous aggregate to a sufficiently high temperature a product definitely recognizable as monoclinic pyroxene is obtained. The supposed inversion is presumably due simply to grain growth and destruction of the fibrous character.

In order to study satisfactorily the change from orthorhombic to monoclinic it was necessary to begin with material that was unquestionably orthorhombic and the natural minerals were the only substances meeting that requirement. The natural pyroxenes used were enstatite from the Bishopville meteorite, enstatite from Espedalen, Norway, bronzite from

---

[8] Allen, Wright, and Clement: This Journal, 22, 385-438, 1906.

[9] This comparison was kindly made for us by Dr. E. Posnjak.

Bonin Islands, bronzite from bronzitite, Jagdlust, South Africa, hypersthene from Mt. Dore, Auvergne, and iron hypersthene from Tunaberg, Sweden. Chemical analyses of these pyroxenes are give in Table III. Natural pyroxenes have the disadvantage that they always contain some constituents other than the components of the system now under investigation, but the enstatites and bronzites used show only moderate amounts of these extraneous oxides. The hypersthenes are not so satisfactory in this respect, especially in their high content of MnO, but the results obtained with them bear such a relation to those obtained with the purer members as to suggest that the impurities do not exert a pronounced effect upon the inversion temperature. For all the iron-bearing materials

TABLE III.

Chemical Composition of Orthorhombic Pyroxenes.

	I	II	III	IV	V	VI
SiO_2	59.97	57.28	55.04	55.40	[48.2]	47.46
TiO_2	...	0.05	...	0.10	...	0.03
Al_2O_3	...	0.90	0.88	1.60	...	0.14
Cr_2O_3	...	...	0.49	0.65	...	...
Fe_2O_3	0.40	0.42	...	nil	...	0.34
FeO	...	6.43	9.40	9.35	28.4	42.23
MnO	...	tr.	0.18	0.15	5.2	3.88
NiO	...	...	...	0.10	...	...
CaO	...	0.13	1.55	0.45	1.5	1.05
MgO	39.34	34.94	32.65	32.45	16.7	5.05
Na_2O	0.74	0.22	...	tr.	...	...
K_2O	tr.	0.01	...	tr.	...	...
H_2O+	...	0.13	0.45	nil	...	0.07
H_2O-	...	...	...	0.15	...	...
P_2O_5	...	...	...	0.20	...	...
CO_2	...	...	...	tr.	...	...
	100.45	100.51	100.64	100.60	[100.0]	100.25

I Enstatite, Bishopville meteorite.
Smith, J. Lawrence, This Journal, 36, 225, 1864.
II Enstatite, Espedalen, Norway.
Washington, H. S., and Merwin, H. E., Am. Min., 8, 64, 1923.
III Bronzite, Bonin Islands.
Kikuchi, Y., Jour. Coll. Sci. Imp. Univ. Japan, 3, 67, 1889.
IV Bronzitite, Jagdlust, Oliphants River, South Africa.
Hall, A. L., Geol. Survey, Union S. Africa Mem. 28, 315, 1932.
V Hypersthene, Mt. Dore, Auvergne, France.
Des Cloizeaux, Min. II, xviii, 1874.
VI Iron-hypersthene, Tunaberg, Sweden.
Sundius, N., Sveriges Geol. Undersök. Årsbok 26, No. 2, p. 6, 1932.

it was necessary to conduct the heating in a sealed, evacuated silica-glass tube in order to avoid oxidation of ferrous iron.

It is especially noteworthy that, while the members approaching the two ends of the series are transformed readily into the monoclinic form, intermediate members experienced definite transformation only with the aid of a "catalyst." Thus the two bronzites can be heated for hours at temperatures more than 300° above their true inversion temperature, even at temperatures where they are partly melted, without visible transformation. That this behavior is due merely to sluggishness of transformation is shown by the fact that, if a very small quantity of NaF is added to these bronzites in the sealed silica tube, the inversion takes place readily at the temperature where it is to be expected from the behavior of other members of the series. We have obtained no light on the manner in which the fluoride accomplishes this result.

Some details of the results may now be pointed out. When enstatite of the Bishopville meteorite is heated at 1150° for 4 hours partial transformation is readily made out. It manifests itself under the microscope as twinned lamellae of the monoclinic form on the edges and corners of the powdered grains. At times small grains are transformed through and through to the twinned form. The twinning is comparatively coarse and the extinction angle against the twinning some 22°. The earlier thermal studies of the relation between clino-enstatite and enstatite led to the conclusion that they were distinct crystalline forms.[10] Some opposition was raised by advocates of the concept of polysymmetry who contended that enstatite was merely clino-enstatite sub-microscopically twinned.[11] The appearance of twinning upon heating would, under this concept, be due to a growth of the twin lamellae from sub-microscopic dimensions. There would naturally be a stage during this growth at which the lamellae would be barely distinguishable under the microscope. Such a stage is never observed. The lamellae are either comparatively coarse or entirely absent and when a grain is partially transformed the boundary between the portion showing coarse lamellae and that showing none is a sharp line. These observations are altogether inconsistent with the concept of polysymmetry, but are in complete agreement with the earlier thermal studies in indicating that enstatite and clino-enstatite are distinct crystalline forms of $MgSiO_3$.

---

[10] Allen, E. T., Wright, F. E., and Clement, J. K.: This Journal, **22**, 391-397, 1906. Wright, F. E.: Z. Krist., **46**, 599-600, 1909.

[11] Zambonini, F.: Z. Krist., **46**, 8, 1908.

When enstatite is heated for as much as 125 hours at a temperature of 1140° (only 10° lower than that at which considerable transformation takes place in only 4 hours) not a trace of monoclinic form is to be found. Such behavior is difficult to reconcile with the monotropic character of enstatite formerly suggested. A monotropic form is always unstable and a 10 degree change of temperature could hardly make such a difference in the rate of change to the stable form. The indications are rather that enstatite is stable up to about 1145° and will persist indefinitely at any temperature below that. On the other hand it will change at a measurable rate at a temperature even a few degrees above 1145°. That enstatite and clino-enstatite are enantiotropic forms with an inversion point at 1145° is the most probable interpretation. We shall find that it is supported by other observations.

The enstatite from Espedalen behaves in a quite similar manner, with the exception that some transformation can be induced at a slightly lower temperature.

Passing over the intermediate members for the moment, and turning to a consideration of the iron-rich members we find the transformation from orthorhombic to monoclinic taking place much more readily. When the temperature of iron-hypersthene from Tunaberg is raised above 960° for as little as ½ hour, complete transformation to the twinned monoclinic form takes place, whereas at 950° no change is observed in 40 hours, from which one can conclude only that there is a definite temperature of inversion at 955° approximately. For the interesting pyroxene upon which the experiments were made we are greatly indebted to Dr. N. Sundius.

In a similar manner a definite point of inversion was fixed for the hypersthene of Mt. Dore. The mineral occurs as small crystals in the vesicles of a lava for a specimen of which we are indebted to Professor Palache. Evidently the crystals of hypersthene occurring in specimens from the locality are not always of the one composition. Warren and Modell have made an X-ray study of the structure of crystals from similar rock specimens also obtained from Professor Palache. They determined the composition by measuring the optical properties, which indicated about 30 per cent $FeSiO_3$.[12] We, likewise, had such a small amount of material as to necessitate optical determination of the composition, but we found much higher refractive indices than did Warren and Modell. Our values, $\gamma = 1.720 - 1.723$ $\alpha = 1.704 - 1.707$, indicate some 47-50 per cent $FeSiO_3$ and suggest that the crystals more nearly correspond with the material from that locality whose analysis is given in standard texts. This analysis has been given in Table III as a general indication of the composition, though their optical properties show that the actual crystals used were somewhat more magnesian. Attention is directed to the rather high content of MnO.

---

[12] Warren, B. E., and Modell, D. I.: Z. Krist., 75, 1-14, 1930.

These crystals are transformed with great readiness to a twinned monoclinic form at any temperature above 1090° but remain unchanged at any lower temperature.

A few remarks should be made as to the orientation of the newly formed monoclinic pyroxene. From the close relationship that Warren and Modell found between orthorhombic and monoclinic pyroxenes in structure one might expect that, upon transformation, the atoms would "click" over into the new position, retaining some prominent direction common to the two structures. This expectation is not usually realized, though in the more magnesian members there is a tendency toward retention of the prism zone. In general, a single crystal or crystal fragment of orthorhombic pyroxene is transformed into an aggregate of several grains of monoclinic pyroxene of random orientation with respect to each other and to the original orthorhombic substance.

To complete the series we shall describe the behavior of the two bronzites investigated. These have nearly the same composition, as shown by the analyses in Table III, and their refractive indices are not measurably different as determined in liquids under the microscope. They have been chosen as representative of two different classes of bronzite. That from Bonin is typical of bronzite as it occurs as phenocrysts in lavas. It is free from twinning. The South African mineral is typical of the bronzites of pyroxenites and related rocks. These usually show a rather obscure lamellar twinning with extinctions up to about 9° against the composition plane. By reason of this inclined extinction they have been regarded as monoclinic by some observers and have been definitely referred to as clino-bronzites.[18] A mere inclined extinction as measured against twinning is not sufficient to disprove orthorhombic symmetry. Twinning on the dome 014 gives such an effect, but in some examples the twinning does not appear to follow that law.[14] However this may be, we wish to point out that these are not clino-bronzites in the strict sense of the term as here employed. True clino-bronzite shows very conspicuous twinning after 100 and the extinction angle is 33° when the composition is that of the two bronzites here investigated.

---

[18] Wagner. Percy A.: South African Journal of Industries, Industries Bulletin Series, Bull. No. 102, p. 17, 1925.

These two bronzites are identical in thermal behavior. They agree in showing extreme reluctance to transformation into the monoclinic form. They fail to invert when heated even to temperatures 300 degrees higher than that at which inversion was to be expected from the behavior of enstatites and hypersthenes and this failure was at first very puzzling. However, when a small quantity of NaF was added to the powdered mineral in the sealed tube, transformation took place readily. In working with added NaF it was found that some monoclinic crystals would form from orthorhombic even at low temperatures where we had every reason to believe that the orthorhombic was the stable form. The formation at low temperatures of a phase stable only at higher temperatures has often been observed, yet even with this complication the stability relations can be made out. In the present instance, for example, NaF causes recrystallization of bronzite to clino-bronzite, and to that form only, at temperatures above 1120°, but below 1120° newly formed crystals of bronzite appear together with the clino-bronzite, which proves the stability of the orthorhombic bronzite at temperatures below 1120° and places the transformation temperature at 1120°.

These several determinations fix the curve *KY* of Fig. 8. Theoretically there should be an inversion interval for all these solid solutions and the first small portion of the newly formed phase should be of different composition from the original material. Actually the interval of temperature (and composition) may be vanishingly small, and the indications are that it is so for the present series. No interval was found during which two phases of different composition persisted and no intimate intergrowth of two phases, such as should be formed in an inversion interval, was made out. On the contrary any grain or portion of a grain which inverted was always transformed completely to a new phase of the same composition as the original. Although these observations indicate no measurable inversion interval the broken curve *KX* has been added to the diagram to indicate a very small inversion interval, in order that the diagram as a whole may have the theoretical form that makes it the more intelligible.

---

[14] It is to be noted that the iron hypersthene of Tunaberg also shows an obscure twinning in certain sections, with extinctions from 4°-12°. Sundius, N., op. cit., p. 5.

Other Solid Phase Relations of Metasilicate Compositions.

Of the changes taking place in the solid state depicted in Fig. 8 the transformation represented by the curves *KY* and *KX* alone is of binary character. The ternary equilibrium indicated by the curve *CY* is concerned with the initial break-down of the clino-pyroxene into olivine and tridymite upon heating. The curve *CY* is located partly by the use of pure synthetic preparations and partly by the use of natural minerals. Thus the mixture $MgSiO_3$ 30 $FeSiO_3$ 70 can be crystallized to a homogeneous clino-pyroxene at temperatures of 1050°-1100°, and if the product is heated at a temperature just above 1150° dissociation takes place with formation of some olivine and tridymite. They appear first as minute crystals of refractive index different from that of the enclosing pyroxene.

Likewise if the natural hypersthene from Tunaberg, Sweden, which is transformed into clino-hypersthene at 955°, be heated only about 5° above that temperature, dissociation of the clino-pyroxene into olivine and tridymite begins.

As a result of such observations the curve *CY* is located, and since its position is based partly upon determinations with pure synthetic preparations, and these are in general agreement with those made upon natural material, it would appear that no great change of solid phase equilibrium is introduced by the presence of the foreign oxides in the natural minerals. Again, the fact that curves *CY* and *KY* come together at *Y* in the appropriate manner suggests that although portions of these curves were determined with the aid of natural minerals the position of the curves on the actual diagram for pure iron-magnesium silicates would not be significantly different and that we are justified in presenting the diagram so determined as that of the pure iron-magnesium silicates.

It was only for some of these low temperature equilibria that it was necessary to resort to the use of natural minerals. All other curves are fixed with the aid of pure synthetic mixtures.

Cooling of Metasilicate Mixtures from the Liquid State.

The manner in which Fig. 8 can be put to use may be brought out by the discussion of the cooling of typical liquids, the attainment of perfect equilibrium being assumed.

A liquid of composition $MgSiO_3$ 90 $FeSiO_3$ 10 begins to crystallize at 1555° with separation of olivine, whose composition cannot be read from the diagram. The olivine continues to crystallize until a temperature of 1545° is attained, when there begins separation of clino-pyroxene of composition $MgSiO_3$ 98 per cent. With further cooling clino-pyroxene separates and olivine is resorbed, until at 1527° the olivine has completely disappeared. The pyroxene now has the composition *B* and the liquid the composition *O* and henceforth the behavior is binary. With further cooling the pyroxene increases in amount and changes in composition along *BS*, while the composition of the liquid changes along *OR*, until at 1500° the pyroxene has the composition $MgSiO_3$ 90 $FeSiO_3$ 10 and the last trace of liquid, now of composition $MgSiO_3$ 70 $FeSiO_3$ 30, vanishes. If the clino-pyroxene is now further cooled it should, if equilibrium were reached, be transformed completely into ortho-pyroxene at 1140°.

The liquid $MgSiO_3$ 70 $FeSiO_3$ 30 begins to crystallize at 1500° with separation of crystals of $MgSiO_3$ 90 $FeSiO_3$ 10. As the temperature falls the crystals change in composition along *BS* and the liquid along *OR* until at 1415° the crystals have the composition $MgSiO_3$ 70 $FeSiO_3$ 30 and the last trace of liquid, now of composition $MgSiO_3$ 45 $FeSiO_3$ 55, vanishes. If the clino-pyroxene is now cooled to 1110° it should invert into the orthorhombic form if equilibrium were reached. The behavior is thus strictly binary throughout.

The liquid $MgSiO_3$ 50 $FeSiO_3$ 50 begins to crystallize at 1440° with separation of crystals of clino-pyroxene $MgSiO_3$ 75 $FeSiO_3$ 25. Upon cooling, the crystals increase in amount and change in composition along *BS* and the liquid changes along *OR* until at 1400° the liquid has the composition *R* and the crystals the composition *S*. Separation of tridymite now begins and crystallization ceases to be binary. Pyroxene and tridymite crystallize through a small interval of temperature and then tridymite begins to be resorbed, until at 1340° the last of the tridymite and of the liquid disappear simultaneously and the charge consists wholly of clino-pyroxene of composition $MgSiO_3$ 50 $FeSiO_3$ 50. Upon cooling to 1085° the clino-pyroxene would invert to ortho-pyroxene if equilibrium were attained.

The liquid $MgSiO_3$ 30 $FeSiO_3$ 70 begins to crystallize at 1455° with separation of tridymite and crystallization is of ternary character throughout. At 1350° tridymite is joined by pyroxene which continues to separate until 1305°, when it reacts with liquid to produce olivine and tridymite, the temperature remaining constant until all the pyroxene has disappeared. Further crystallization of olivine and tridymite then occurs until the liquid has entirely disappeared at 1295°. The crystalline aggregate of olivine and tridymite remains as such until 1285°, where reaction between them begins, with resultant formation of clino-pyroxene. This reaction continues until the temperature reaches 1150°. Combination is then complete and the mass consists entirely of clino-pyroxene of composition $MgSiO_3$ 30 $FeSiO_3$ 70. Upon cooling the clino-pyroxene to 1020° it would be transformed into ortho-pyroxene if equilibrium were reached.

The liquid $MgSiO_3$ 10 $FeSiO_3$ 90 begins to crystallize at 1530° with separation of cristobalite which continues to form until 1470°, where it is transformed into tridymite. Tridymite continues to separate until the temperature has reached 1240°, when olivine forms in addition, and the two crystallize until the temperature is 1220°, when crystallization is complete. Cooling to 1010° results in the beginning of reaction between olivine and tridymite to form clino-pyroxene which continues down to 955°. At this temperature the clino-pyroxene, now of composition Y, is transformed into ortho-pyroxene of composition X and the crystalline aggregate of olivine, tridymite, and ortho-pyroxene persists indefinitely at lower temperatures except that at 870° tridymite is transformed to quartz.

A SERIES OF ISOTHERMAL PLANES.

The salient features of the equilibrium relations of the metasilicate and of the orthosilicate solid solutions, individually, have now been pointed out. Although some aspects of the relations between the two series have been brought out by means of the metasilicate section, a complete picture of the composition of all the phases concerned in the equilibria is gained only with the aid of ternary figures. We shall therefore present a series of isothermal planes.[15]

---

[15] These figures, representing isothermal planes, are all drawn to true scale, the composition of all phases (including the solid solutions but excepting the magnesio-wüstites) being determined by the experimental results. Further information regarding these determinations is given under the head "Three Phase Triangles and Three Phase Boundaries."

The first to be discussed is that for 1550°, Fig. 9. At this temperature the liquid *a*, which is of orthosilicate composition, is in equilibrium with olivine whose composition lies at the point at the other end of the brace joining it with *a*. The equilibrium is binary, the brace being the device here adopted to indicate binary equilibrium. All the liquids *a-b* are in equilibrium with olivine, each with an olivine of different composition as indicated by the tie-lines. Any mixture whose composition is represented by a point in the triangle *aob* thus consists at 1550° of olivine and liquid, the composition of each of which is indicated by the ends of the tie-line passing through the point of composition of the mixture.

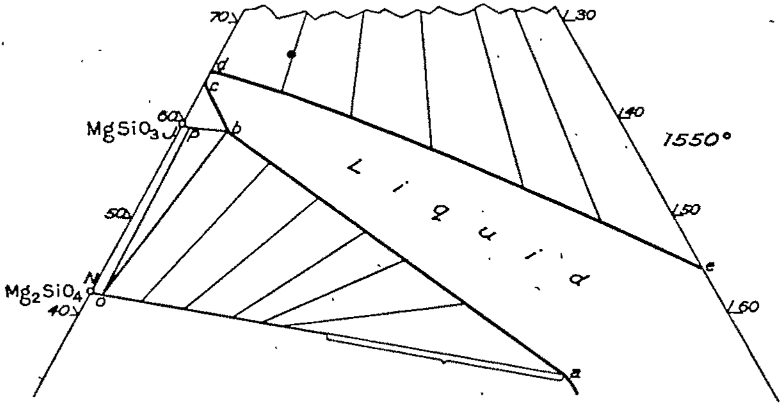


Fig. 9. Phase relations at 1550°. Truncated SiO_2 apex = *T* in text. Cf. Fig. 11.

The liquid *b* is in equilibrium with both the olivine *o* and the pyroxene *p* and is therefore a point in the boundary curve *KL* of Fig. 5. All mixtures lying in the triangle *pbo* consist at 1550° of the three phases, liquid *b*, pyroxene *p*, and olivine *o*.

The liquids *b* to *c* are in equilibrium with clino-pyroxenes varying in composition from *p* to *J* and all mixtures in the area *cbpJ* thus consist at 1550° of liquid between *b* and *c* and pyroxene between *p* and *J*. Tie-lines are here omitted to avoid crowding.

The mixtures in the area *JpoN* are completely crystalline at 1550° and consist of pyroxene *p* to *J* and olivine *N* to *o*.

The liquids *d* to *e* are in equilibrium with cristobalite at 1550° and all mixtures in the triangle *deT* consist at 1550° of cristobalite and liquid whose composition is given by the tie-line passing through the point indicating the total composition of the mixture. The tie-lines are thus lines radiating from the SiO_2 apex here truncated to save space, but called *T* in this and subsequent figures.

The next isothermal plane (Fig. 10) is that for 1527°, the temperature of the point *O* of Fig. 5 at which the metasilicate join crosses the pyroxene-olivine boundary curve. The point is lettered *O* in Fig. 10 also. It is not an invariant point but is merely a limiting case of points having the properties of *b* in Fig. 9. The liquid *O* is in equilibrium with the pyroxene *p* (a binary relation indicated by a brace) and also with the olivine *o*. The liquids *O* to *c* are in equilibrium with pyroxenes *p* to *p′*. The liquid *c* is in equilibrium with the pyroxene *p′* and with cristobalite. All mixtures in the triangle *cp′T* consist of the three phases pyroxene *p′*, cristobalite, and liquid *c*. All mixtures in the triangle *p′JT* consist of the two phases cristobalite and a pyroxene between *p′* and *J*. All other areas have the same properties as their analogues in Fig. 9.

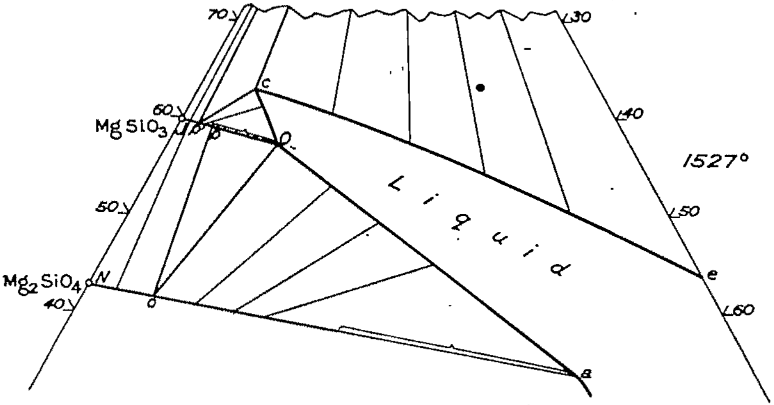


Fig. 10. Phase relations at 1527°. Truncated SiO_2 apex = *T* in text.

The next isothermal plane, Fig. 11, is that for 1450°. All other figures of this character have been limited on the low-silica side by the orthosilicate join and have been truncated on the high-silica side. In the present example the full triangle is shown in order to make clear the general appearance of the completed figures. This particular temperature is so treated because it is the only one at which the equilibrium involving magnesio-wüstite has been approximately determined.

The liquids *f* to *g* are in equilibrium with magnesio-wüstites and the liquid *f* is in equilibrium with both magnesio-wüstite *h* and olivine *o'*. The liquids *f* to *a* to *b* are in equilibrium with olivines.

One special feature may be pointed out. At 1527° (see Fig. 10) the pyroxene *p'*, which is in equilibrium with SiO_2 and liquid, is more magnesian than the pyroxene *p*, which is in equilibrium with olivine and liquid. At 1400° (see Fig. 12) the opposite condition prevails, i.e., the pyroxene *S*, which is in equilibrium with SiO_2 and liquid, is less magnesian than the pyroxene *p*, which is in equilibrium with olivine and liquid. At some intermediate temperature, therefore, SiO_2 and liquid on the one hand and olivine and liquid on the other will be in equilibrium with the same pyroxene. Our determinations do not enable us to state definitely the temperature at which this condition prevails, but they indicate that it is probably not far from 1450°. In Fig. 11, therefore, the liquid *c* and SiO_2

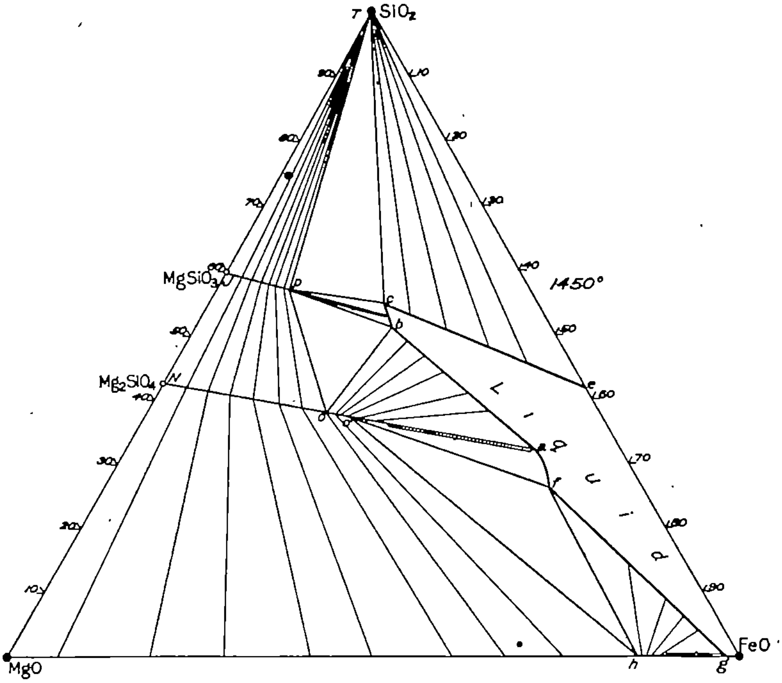


Fig. 11. Phase relations at 1450°.

(tridymite) and also the liquid *b* and olivine *o* are shown in equilibrium with the same pyroxene *p*.

The next isothermal plane (Fig. 12) is that for the temperature 1400°, the temperature of the point *R* of Figs. 5 and 8, which is not an invariant point but merely the point of intersection of the pyroxene-tridymite boundary curve with the metasilicate join. The liquid *R* is in equilibrium with the pyroxene *S* (the binary relation indicated by the same letters in Fig. 8) and with tridymite. All other areas have the properties of their analogues in former figures.

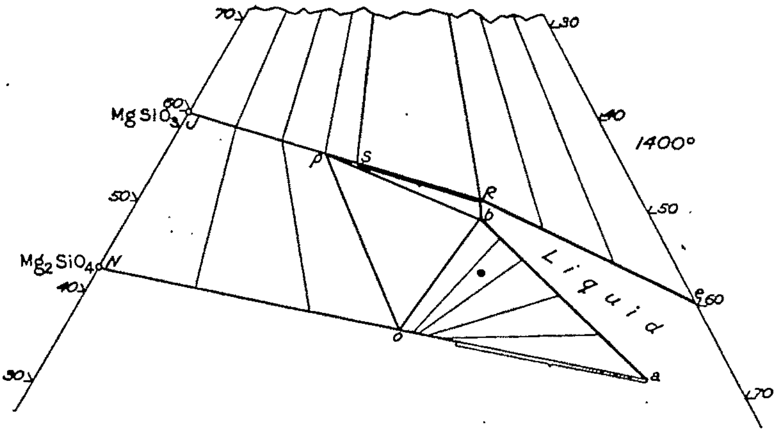


Fig. 12. Phase relations at 1400°. Truncated SiO_2 apex = *T* in text.

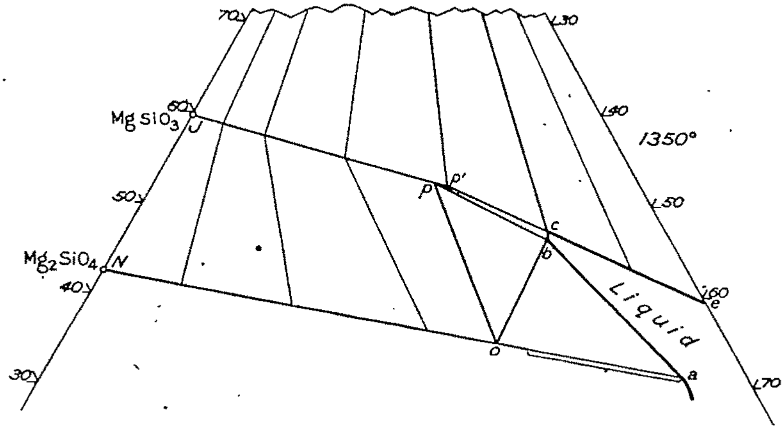


Fig. 13. Phase relations at 1350°. Truncated SiO_2 apex = *T* in text.

The next isothermal plane (Fig. 13) is that for 1350°, which

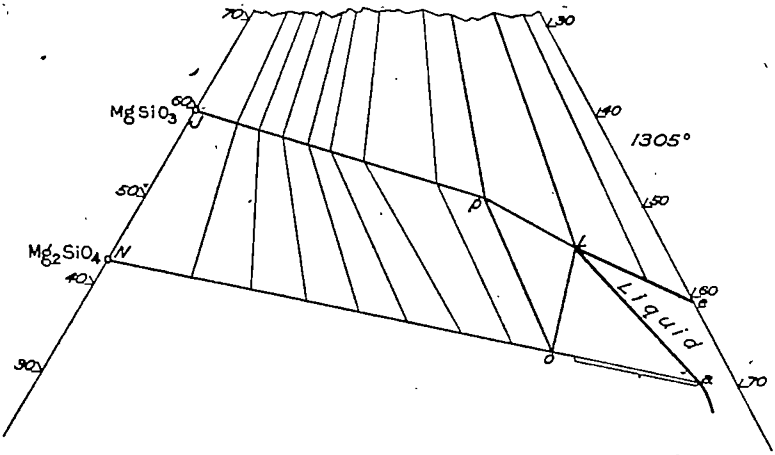


Fig. 14. Phase relations at 1305°. Truncated SiO_2 apex $= T$ in text.

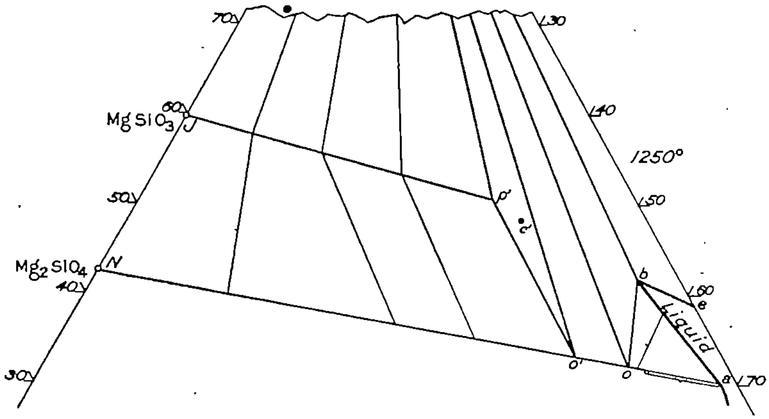


Fig. 15. Phase relations at 1250°. Truncated SiO_2 apex $= T$ in text.

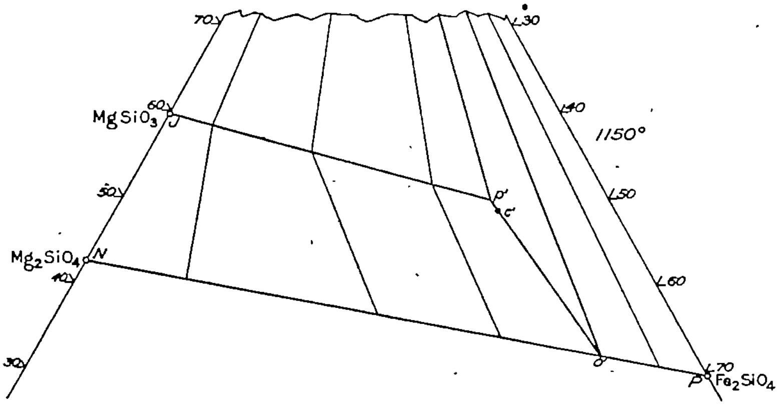


Fig. 16. Phase relations at 1150°. Truncated SiO_2 apex $= T$ in text.

is typical of those temperatures between 1400° and 1305° where both the liquid *c*, in equilibrium with pyroxene *p'* and tridymite, and the liquid *b*, in equilibrium with the pyroxene *p* and olivine *o*, lie on the low-silica side of the metasilicate join. The areas require no special discussion.

The next isothermal plane (Fig. 14) is that for 1305°, the temperature of the invariant point *L* of Fig. 5 which is again lettered *L* in the present figure. The liquid *L* is in equilibrium with the three solid phases with which it is joined, viz., olivine *o*, pyroxene *p*, and tridymite *T*. At a temperature immediately below 1305°, pyroxene ceases to be stable in contact with liquid. The line *pL* therefore disappears and its place is taken by *oT*.

The next isothermal plane (Fig. 15) is that for 1250°, typical of those temperatures where only olivine and tridymite are in equilibrium with liquid. The liquid *b* is that in equilibrium with both these phases, the olivine having the composition *o*. The triangle *boT* includes the composition of all mixtures that consist of the three phases, liquid *b*, olivine *o*, and tridymite *T*. The adjacent triangle *oo'T* includes all mixtures that consist of only the two phases, tridymite *T* and an olivine between *o* and *o'*. The triangle *o'p'T* is again a three-phase triangle, in this instance all three phases being solid, the olivine *o'*, the pyroxene *p'*, and tridymite *T*.

The next isothermal plane (Fig. 16) shows the relations at 1150°, a temperature at which no liquid forms in any mixture of the system. There is only one three-phase triangle, the three-solid-phase triangle *o'p'T* which includes all mixtures that consist of the three phases, olivine *o'*, pyroxene *p'*, and tridymite *T*.

The next isothermal plane (Fig. 17) is that for 1050°, typical of temperatures where two different kinds of pyroxene co-exist in equilibrium. The triangle *o''p''p'''* is a three-solid-phase triangle which includes all mixtures that consist of olivine *o''*, ortho-pyroxene *p''*, and clino-pyroxene *p'''*. The three-solid-phase triangle *p''p'''T* includes all mixtures that consist of the same two pyroxenic phases and tridymite. The three-solid-phase triangle *o'p'T* has the same properties as its analogue in Figs. 15 and 16. All other areas are two-phase areas. Thus the area *JNo''p''* includes all mixtures that consist of the two phases, olivine between *o''* and *N* and ortho-pyroxene between *p''* and *J*. The area *o''o'p'p'''* includes all mixtures that consist of the two phases, olivine between

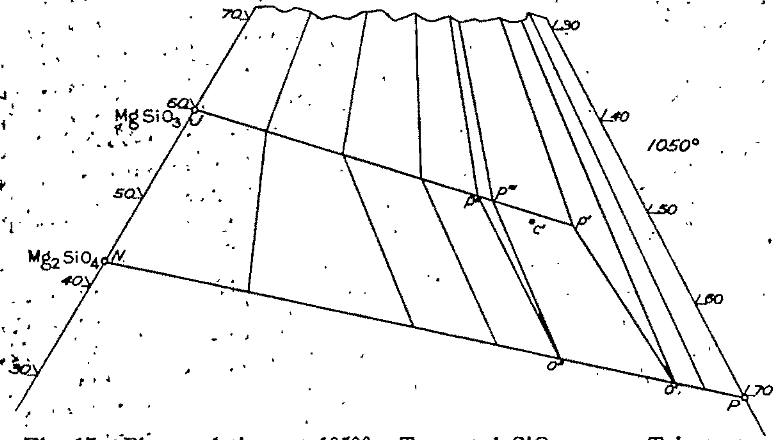


Fig. 17. Phase relations at 1050°. Truncated SiO_2 apex = *T* in text.

o'' and *o'* and clino-pyroxene between *p'''* and *p'*. With this explanation no discussion of the other areas is necessary.

The next isothermal plane (Fig. 18) is that for 955°, which is the temperature of the invariant point at which four solid phases coexist, the horizontal *XYZ* of Fig. 8. The points *X* and *Y* of Fig. 18 correspond with the points similarly lettered in Fig. 8. The four solid phases in equilibrium are ortho-pyroxene *X*, clino-pyroxene *Y*, olivine *o*, and tridymite *T*. This temperature is the lowest temperature of stable existence of pure ferromagnesian clino-pyroxene. Immediately above 955° the triangle *TYo* represents the stable configuration. Immediately below 955° the triangle *TXo* represents the stable configuration.

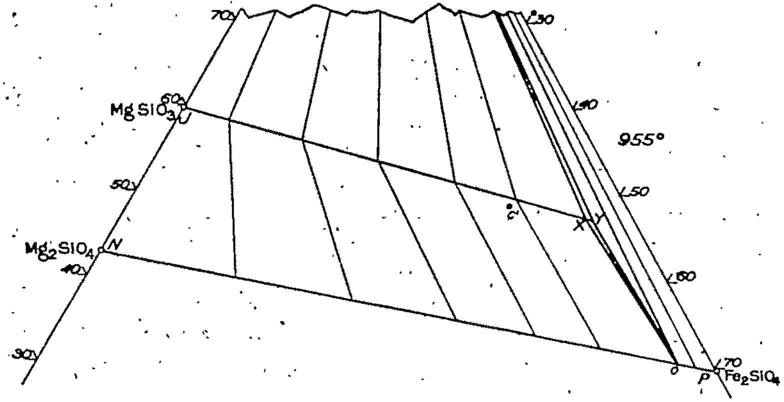


Fig. 18. Phase relations at 955°. Truncated SiO_2 apex = *T* in text.

THREE-PHASE TRIANGLES AND THREE-PHASE BOUNDARIES.

In the isothermal figures there are numerous examples of liquids that are in equilibrium with two solid phases. The point indicating the composition of the liquid is the apex of a three-phase triangle, the two points at the ends of the base indicating the composition of the two solid phases. The sides of a three-phase triangle are called three-phase boundaries and are to be carefully distinguished from boundary curves. The three-phase triangles referring to the equilibrium between liquid, olivine, and pyroxene are of greatest interest in the present system. These are the triangles *bop* of Figs. 9-14.[16] It is important to note that any point in the three-phase boundary *bo* of any one of these figures represents a mixture which consists of liquid *b* and olivine at the temperature at which the individual diagram applies. Any such mixture cooled from the liquid state has therefore experienced separation of olivine and has just arrived at a temperature where separation of pyroxene begins. Similarly, any mixture represented by a point in the three-phase boundary *bp* consists of liquid and pyroxene and has just arrived at a temperature where separation of olivine begins. Moreover, any point in the three-phase boundary *op* (the base of the three-phase triangle) of these several figures represents a mixture consisting of pyroxene *p* and olivine *o* and, if cooling, has just reached that condition, i.e., the last trace of liquid has just disappeared. Obviously it is necessary to know the position of these three-phase boundaries in order to be able to describe accurately the course of crystallization of any mixture. One method of determining these three-phase boundaries is to hold a mixture at a temperature at which it consists of liquid with some olivine and pyroxene crystals and to determine optically the composition of both olivine and pyroxene. This gives the two points at the ends of the base of the three-phase triangle. Since the composition of the liquid lying on the boundary curve at all temperatures has been previously determined, the apex of the three-phase triangle for the temperature of the experiment is known and therefore the complete triangle. Such determinations have been made upon a number of mixtures at different temperatures. It is with these as basis and, of course, similar determinations for other types of

---

[16] There is no triangle *bop* in either Fig. 10 or Fig. 14, but the triangles *Oop* and *Lop* of these figures respectively are limiting cases of the triangle *bop* and have the same properties.

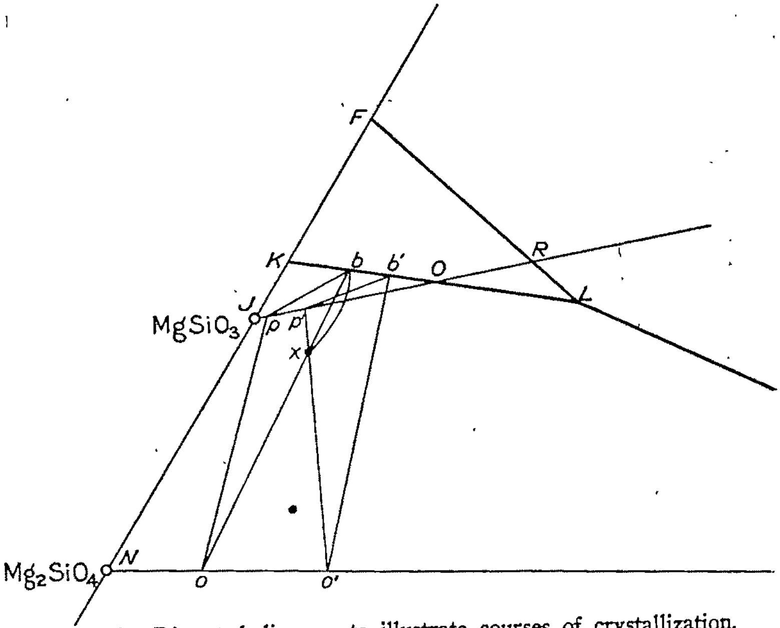


Fig. 19. Distorted diagram to illustrate courses of crystallization.

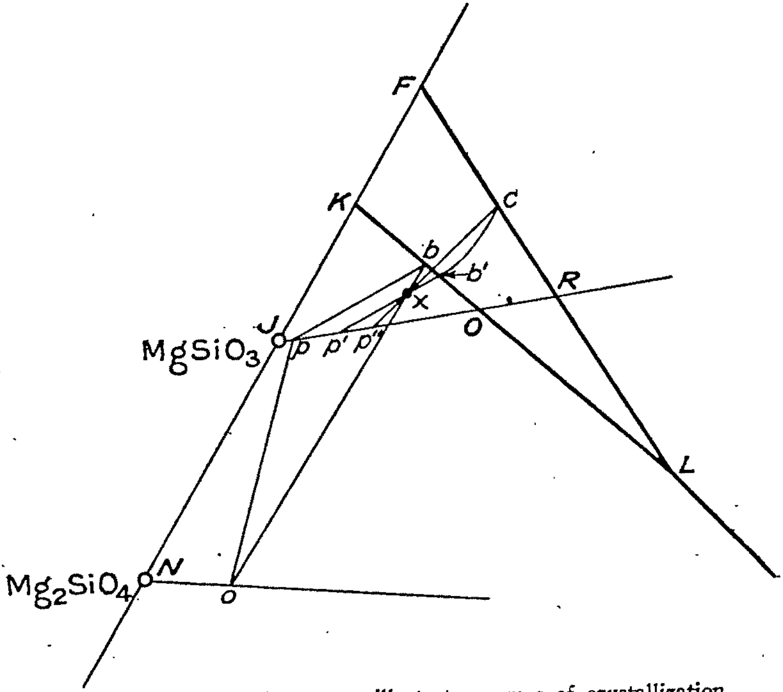


Fig. 20. Distorted diagram to illustrate courses of crystallization.

three-phase triangles, that the several isothermal figures 9-18 have been drawn. They are drawn to scale and solid-phase compositions may be read from them. No table of such compositions is given, since they do not lend themselves to presentation in such form.

A more extended discussion of the general properties of three-phase triangles is given in the paper on the system, CaO-FeO-SiO_2.[17]

COURSES OF CRYSTALLIZATION.

With this preliminary explanation of the method of determination and of the full significance of the three-phase boundaries of the isothermal figures, we may proceed to discuss the crystallization of typical liquids. For this purpose it is, in some instances, necessary to use a distorted diagram on account of the confusion of lines and points that would otherwise result. Fig. 19 is such a distorted diagram on which the several points and curves have been lettered in accordance with the plan used in the isothermal figures 9-18. A mixture of composition x (Fig. 19) begins to crystallize with separation of a highly magnesian olivine of composition represented by a point between o and N. The liquid follows the curved course xb,[18] reaching the boundary curve KL at b when the olivine has attained the composition o, the line ob being the three-phase boundary (of the ob type of Figs. 9-14) which passes through x. At the temperature of b pyroxene of composition p begins to crystallize, bp being a three-phase boundary of the bp type of Figs. 9-14. With further cooling the liquid changes along the boundary curve KL, pyroxene separating and olivine being resorbed and both being changed continuously in composition. At b' the last trace of liquid disappears, $o'p'$ being the base of the three-phase triangle or the three-phase boundary (of the op type of Figs. 9-14) which passes through x, and b' being its apex. The mass then consists entirely of pyroxene p' and olivine o'. The pyroxene which forms directly from liquid is in all mixtures of this system, clino-pyroxene. Upon cooling it is transformed, at equilibrium, to ortho-pyroxene but we shall not follow the majority of the mixtures discussed beyond the stage where they first become completely crystalline. On a later page the changes in the solid state will be followed for one mixture, by way of illustration of the use of three-solid-phase triangles.

---

[17] Bowen, N. L., Schairer, J. F., and Posnjak, E.: Op. cit., p. 233 ff.

[18] Necessarily curved because the composition of the olivine is continually moving along No towards o.

The mixture x of Fig. 19 is typical of those that exhibit partial but incomplete resorption of olivine. We shall now discuss a mixture which is typical of those that exhibit complete resorption of olivine. The mixture x of Fig. 20 (also a distorted diagram) is of this latter character. Cooled from the liquid state, it precipitates olivine first and the composition of the liquid follows a curved course to the boundary curve KL at b, at which time the olivine has the composition o. Pyroxene of composition p then begins to separate and the liquid moves along the boundary curve, pyroxene separating and olivine being resorbed. When the liquid has reached the composition b', such that the three-phase boundary $p'b'$ passes through x, the mixture now consists only of pyroxene p' and liquid, i.e., the olivine has been completely resorbed. The liquid

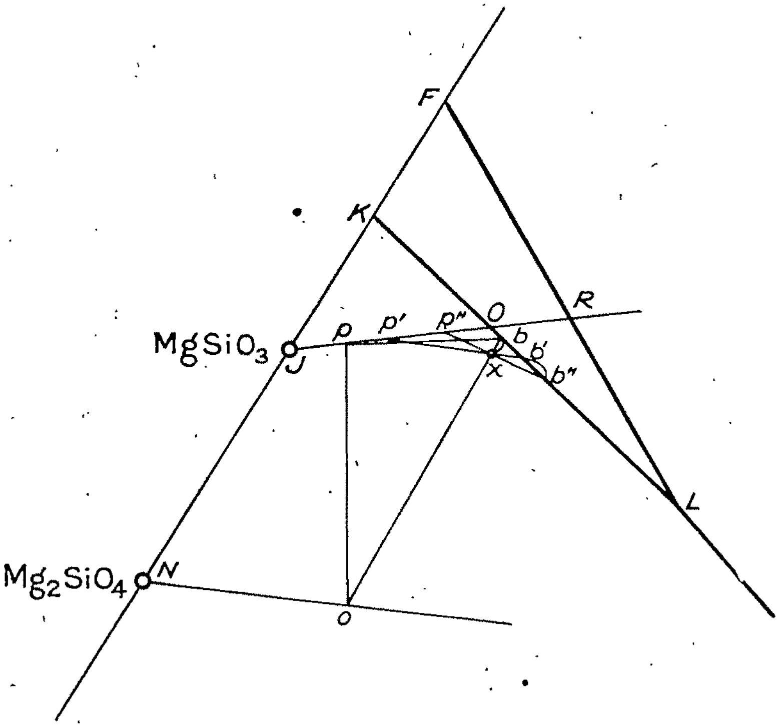


Fig. 21. Distorted diagram to illustrate courses of crystallization.

now crosses the pyroxene field on the curved course $b'c$. At c the pyroxene has the composition p'', the line $p''c$ being a three-phase boundary of the type $p'c$ of Figs. 10 and 11.[19] From the liquid c cristobalite begins to separate and the liquid changes along the boundary curve towards R, both pyroxene and cristobalite separating until the liquid is exhausted, at which time the liquid has a composition between c and R not far removed from c. The actual point and the construction lines that determine it are not given on account of the confusion of lines that results, but it is the apex of the three-phase triangle (of the type of cpT of Fig. 11) whose base (of the type Tp of Fig. 11) passes through x.

The liquid x of Fig. 21 is typical of a small area of liquids in the angle JOL of Fig. 5. Again a distorted diagram is necessary. Crystallization begins with separation of olivine and the liquid follows the curved course xb. When the liquid has the composition b the olivine has the composition o and pyroxene of composition p begins to separate. The liquid now moves along the boundary curve towards L, pyroxene separating and olivine being resorbed. When the liquid has reached the composition b', whose position is determined by the three-phase boundary (of the pb type of Figs. 9 and 10) which passes through x, the pyroxene has the composition p' and the olivine is completely resorbed. The liquid now leaves the boundary curve and moves into the pyroxene field, pyroxene alone separating. The liquid follows the curved course $b'b''$ which brings it back to the boundary curve at b''. The position of b'' is determined by another three-phase boundary (also of the pb type of Figs. 9 and 10) which passes through x. Olivine now begins to crystallize again and separates together with pyroxene until crystallization is complete. The last minute quantity of liquid has the composition represented by a point on the boundary curve between b'' and L (not indicated in the diagram), the position of the point being determined as the apex of the three-phase triangle (of the type bpo) whose base (of the type po) passes through x. Only a very small area of liquids represented by points in the angle JOL have two different three-phase boundaries of the pb type passing through them, and the range of liquids which show this precipitation, complete resorption, and reprecipitation of olivine is therefore much restricted. There is, however, a considerable range of composition of liquid, of which points in *bo* between *x* and *o* are representative, that shows incomplete resorption of olivine followed by a period of renewed precipitation of olivine.

---

[19] In Fig. 11 p and p' fall at one point which is lettered p.

The crystallization of a great many liquids can be discussed satisfactorily with the aid of an undistorted or true-scale diagram. Fig. 22 is of this character. With its aid we may discuss the crystallization of a number of mixtures in the olivine field which have characteristics somewhat different from those of mixtures in that field that have already been discussed. The liquid *x* begins to crystallize with separation of olivine and follows the curve *xb*. When the liquid has the composition *b* the olivine has the composition *o* and pyroxene of composition *O* begins to crystallize. Not only pyroxene but olivine also continues to separate (no resorption of olivine) the liquid following the boundary curve to *b′* when the pyroxene has the composition *p*, the olivine the composition *o′*, and the last trace of liquid has just disappeared (since *po′* passes through *x*). Mixtures lying in the three-phase boundary *ob* (of which *x* is typical) are the first mixtures that fail to show resorption of olivine, i.e., all mixtures to left of *ob* in the olivine field do show resorption of olivine whereas all mixtures to the right do not. The reason for this situation is that liquids to the right of *b* on the boundary curve are in equilibrium with olivine and with a pyroxene to the right of *O*, on the metasilicate join, that is, with two solid phases that lie on opposite sides of the boundary curve,[20] and movement along the boundary curve is accomplished by subtraction of both these solid phases. On the other hand, liquids to the left of *b* on the boundary curve are in equilibrium with olivine and with a pyroxene to the left of *O*, i.e., between *J* and *O*. They are thus in equilibrium with two solid phases that lie on the same side of the boundary curve and movement along the boundary curve can thus be accomplished only with resorption of the olivine and separation of pyroxene. Because all mixtures to the right of *ob* show only simple subtraction of both olivine and pyroxene from the liquid and all liquids to the left of *ob* show, at some stage, resorption of olivine, it is not to be assumed that liquids to the left of *ob* never show simple subtraction of both olivine and pyroxene. Some of them do in the final stages of their crystallization, as we have seen in the discussion of mixtures referred to Fig. 21.

---

[20] Since the boundary curve is sensibly a straight line there is no need to speak of the tangent to it.

The mixture x' of Fig. 22 begins to crystallize with separation of olivine, and the liquid follows the curved course $x'b'$. At b' the olivine has the composition o', pyroxene of composition p begins to separate, and the liquid moves along the boundary curve to L. At L the olivine has the composition o'' and the pyroxene a composition, for all practical purposes, coincident with R. Since $o''R$, the base of the three-phase triangle, passes through x', the mass consists entirely of the two solid phases, and the liquid, now of composition L, has vanished.

The mixtures x'', x''' and x'''' will, of course, still have some liquid of composition L when they reach the temperature L because they lie within the three-phase triangle $Ro''L$. The liquid L will then react with pyroxene to produce olivine and tridymite, the temperature remaining constant meanwhile. In the case of mixture x'' the liquid will be consumed by this reaction and the completely crystalline mass will consist of olivine o'', pyroxene R and tridymite T. In the case of mixture x''' pyroxene and liquid are exhausted simultaneously and the mass consists of olivine o'' and tridymite T. In the case of mixture x'''' some liquid remains when the pyroxene is consumed. The liquid changes in composition along LM, olivine and tridymite separating. Crystallization is complete when the liquid has reached the composition b'' and the olivine the composition o''', the base $o'''T$ of the three-phase triangle $b''o'''T$ passing through x''''.

The olivine o'' is plainly the most magnesian olivine that can form in equilibrium with free silica in the present system at atmospheric pressure. It has about 32 per cent Mg_2SiO_4.

We may now turn to the crystallization of liquids in the pyroxene field. The liquid y of Fig. 22 begins to crystallize with separation of pyroxene of composition between p' and J and the liquid follows the curved course yc to the boundary curve. When the liquid has the composition c the pyroxene has the composition p' and cristobalite begins to separate, $p'c$ being the three-phase boundary of the type so lettered in Fig. 10. The liquid then moves along the boundary curve with separation of both pyroxene and cristobalite until the liquid has the composition G, when cristobalite changes to tridymite. The liquid then moves along the boundary curve GL and is finally consumed when it has a composition represented by a point not far from G. The position of the point is determined as the apex of the three-phase triangle (of the *pTc* type of Fig. 11) whose base (of the *pT* type of Fig. 11) passes through *y*.

No other mixtures in the pyroxene field will be discussed except those that show features of particular interest. Among these are included all mixtures whose crystallization is such that at some stage the liquid moves along the portion *RL* of the boundary curve *GRL*. A distorted diagram, Fig. 23, is necessary for the discussion of these. In it curves are lettered to correspond with those in the undistorted diagram (Fig. 22) and the relations depicted are readily transferred mentally to the undistorted figure.

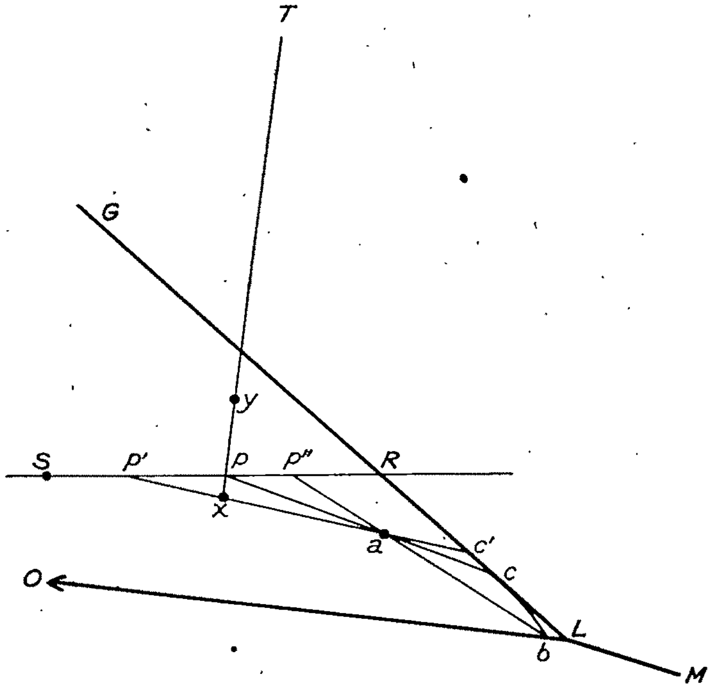


Fig. 23. Distorted diagram to illustrate courses of crystallization.

The mixture *p* of Fig. 23 is of metasilicate composition. Its crystallization can therefore be read from Fig. 8 but not in full detail, for at certain stages the equilibrium is ternary and the composition of some phases appearing at these stages is incapable of expression in Fig. 8. In Fig. 23, on the other hand, all phases can be depicted. Thus the liquid p begins to crystallize with separation of clino-pyroxene somewhat more magnesian than S and the liquid, maintaining metasilicate composition, moves along pR to R, at which temperature the crystals have the composition S. Now crystallization of tridymite begins and the liquid follows the boundary curve RL. When the liquid has attained the composition c' the pyroxene has the composition p', $c'p'$ being a three-phase boundary of the type cp' of Fig. 13. The proportions of the three phases, liquid c', pyroxene p', and tridymite T are determined by the position of the point p within the three-phase triangle $p'c'T$. In particular the proportion of tridymite is given by the ratio $\frac{px}{Tx}$, x being the point of intersection of $p'c'$ and Tp produced. When the liquid has attained the composition c, the pyroxene has attained the composition p, cp being again a three-phase boundary of the same type. But since p lies in the base pT of the three-phase triangle the liquid is reduced to zero when it has attained the composition c and, since p lies at the end of the base, the tridymite is likewise reduced to zero. Thus both tridymite and liquid are finally consumed when the liquid has the composition c and the whole mass then consists of the pyroxene p. As the liquid changes from R to c there is, then, at first an increase of tridymite from its initial value of zero, passage through a maximum value and then final return to zero. The maximum proportion of tridymite will obviously occur when the value of the intercept px and therefore of the ratio $\frac{px}{Tx}$ passes through a maximum as the three-phase boundary passes from the position SR, through $p'c'$, to the position pc.

The crystallization of the liquid y is in some respects related to that of the liquid p. Crystallization begins with the separation of pyroxene somewhat more magnesian than S. The liquid follows a curved course to the boundary curve GR where crystallization of tridymite begins. The liquid then moves along the boundary curve with separation of both tridymite and pyroxene. When the liquid has the composition R (1400°) the pyroxene has the composition S, and the third phase is tridymite T. The proportion of tridymite at this temperature is given by the ratio $\frac{yp}{Tp}$. With further cooling the liquid moves towards L. When it has attained the composition c', the pyroxene has the composition p' and the proportion of tridymite is given by the ratio $\frac{yx}{Tx}$, which is greater than $\frac{yp}{Tp}$. When the liquid attains the composition c, the pyroxene has the composition p. The amount of liquid has therefore been reduced to zero and the mass consists entirely of tridymite T and pyroxene p. The proportion of tridymite is again $\frac{yp}{Tp}$, the same as it was at 1400°. During the fall of temperature and change of composition of liquid from R to c the proportion of tridymite plainly passes through a maximum and this maximum is at the same temperature as that for the liquid p already discussed, since it likewise depends on the maximum value of the changing intercept xp, or more specifically xy, which is xp plus the constant yp.

From the above discussion it will be clear that for all mixtures on the three-phase boundary Tp there is a certain temperature and composition of the liquid between R and L at which the proportion of tridymite passes through a maximum, i.e., separation of tridymite ceases and its resorption begins. Moreover, this is the same temperature (and composition of the liquid) for all these mixtures lying in Tp. For any other mixture such as p' or one lying in $p'T$ there is likewise a temperature of maximum proportion of tridymite but it is a different temperature (and composition of the liquid) from that obtaining for mixtures lying in pT. Thus the reaction that takes place *at any point* in the curve RL may be different for different total compositions of the mixtures concerned, that is, for different proportions of the three phases concerned, the compositions of the individual phases being necessarily the same in all cases. At a certain temperature tridymite will be *subtracted from* the liquid if the total composition (in other words the relative proportions of the three phases) has a certain value, and at the same temperature tridymite will be *added to* (resorbed by) the liquid if the proportions have a certain different value.

There is yet another type of mixture whose course of crystallization falls, in part at least, along the portion RL of the boundary curve. The metasilicate mixture p and the mixture y with excess silica over the metasilicate ratio have been discussed. We shall now turn to a mixture with a lower proportion of silica. Such a mixture is represented by a (Fig.

23). A liquid of composition *a* begins to crystallize with separation of pyroxene of composition approaching *S* and follows a curved course which meets the boundary curve at *c*′, the pyroxene then having the composition *p*′. At *c*′ tridymite begins to separate and the liquid moves along the boundary curve. After a short period of separation, tridymite begins to be resorbed and when the liquid has the composition *c* resorption is complete, the mass consisting entirely of pyroxene *p* and liquid *c*. The liquid now leaves the boundary curve and passes across the pyroxene field on the curved course *cb* with continued separation of pyroxene until the boundary curve *OL* is encountered at *b*. Here olivine begins to separate, *bp*″ being a three-phase boundary of the *bp* type of Fig. 13. With separation of both olivine and pyroxene the liquid moves along the boundary curve toward *L*. Further crystallization need not be discussed since it depends upon factors already considered in connection with the points *x*′, *x*″, *x*‴, and *x*⁗ of the true-scale diagram, Fig. 22.

The liquid *a* (Fig. 23) is typical of those mixtures in the angle *SRL* through which pass two three-phase boundaries of the *pc* type.

It is to be noted that a liquid of the composition *c*′, when entirely free from crystals, moves along the boundary curve with separation of pyroxene and tridymite, passes through *c* still following the boundary curve, and effects resorption of tridymite which is not complete until the liquid has attained the composition *L*. The mass now consists of pyroxene *R* and liquid *L*, the ultimate three-phase boundary of the *pc*′ type coinciding sensibly with *RL*. We may follow further crystallization of *c*′ by referring back to the true-scale diagram, Fig. 22, upon which the composition *c*′ has been marked. From this figure it is plain that the pyroxene *R* reacts with the liquid *L* to produce olivine *o*″ and tridymite. In other words, tridymite, which had been completely resorbed, now reappears and the temperature remains constant at *L* until the pyroxene has disappeared. The liquid then moves along the boundary curve *LM* with separation of olivine and tridymite until the liquid has the composition *b*″, at which time crystallization is complete and the mass consists of olivine *o*‴ and tridymite. Recapitulating, we find that tridymite appears, disappears, and reappears, pyroxene appears and disappears upon formation of olivine and tridymite from it, and if we follow the completely crystallized product to lower temperatures we find olivine and tridymite recombining to pyroxene. This is a truly remarkable complexity of behavior for a mixture of only three components.

Three-Solid-Phase Triangles.

We may illustrate the use of three-solid-phase triangles by following in detail the solid reactions taking place in the cooling mixture c' which we have already referred to in brief above. This may be done with the aid of Figs. 15-18 upon each of which the composition c' has been indicated. It will be noted that at 1250° (Fig. 15) the point c' lies in the three-solid-phase triangle $p'o'T$. The reaction between olivine and tridymite to produce pyroxene has, therefore, already gone on to a considerable extent.[21] At 1150° (Fig. 16) the point c' lies in the side $p'o'$ of the three-solid-phase triangle $p'o'T$. The reaction between olivine and tridymite has therefore just reached completion, tridymite being entirely consumed and the mass consisting mainly of pyroxene p' with a little olivine o'. At 1050° (Fig. 17) the point c' lies in the two-phase area $p'o'o''p'''$. The mass has experienced no change of condition from that obtaining at 1150° and still consists of the two phases olivine and clino-pyroxene. At 955° (Fig. 18) the point c' lies in the two-phase area $NJXo$. The mixture therefore consists of olivine and ortho-pyroxene, the change from clino- to ortho-pyroxene having occurred when the three-solid-phase triangle $p''p'''o''$ of Fig. 17 traversed the point c' in the migration of the triangle to the right with falling temperature.

Other Type of Three-Phase Triangle.

For completeness it is desirable to mention one other type of three-phase triangle necessary to the full description of equilibrium in the system. Three-phase triangles of this type refer to equilibrium in which two liquid phases and one crystalline phase are concerned. Cristobalite is the only crystalline phase that can occur in contact with two liquids, and the triangle valid for any given temperature has, therefore, as one apex the SiO_2 corner (A, Fig. 5) and as the other apices a point in BC and a point in DE representing the two liquids in equilibrium with each other at that temperature. Since the tie-lines crossing the area $BCED$ and joining liquids in equilibrium with each other are not determined, the details of such triangles cannot be pursued further.

---

[21] The reaction began, of course, when the side $o'T$ of the triangle $p'o'T$ passed through c' in its migration to the right with falling temperature.

OPTICAL PROPERTIES OF PHASES.

The identification of phases present in the product of any experiment is an essential part of an investigation of the kind here described. This was done by determining their optical properties with the aid of the petrographic microscope. A glassy phase was readily distinguished from crystals and the different kinds of crystals were distinguished from each other by exact measurements of optical constants. This permitted not only a determination of the phase but also, in the case of crystalline phases of variable composition (solid solutions), a rather close fixing of its composition. In order to determine the composition of a crystalline phase by optical means it is, of course, essential to know the manner of variation of optical properties with composition. Measurements must, therefore, be made upon crystals of known composition. These are best prepared by using a mixture of known proportions which can be induced to crystallize entirely to one phase, which phase will then necessarily have the composition of the mixture.

Magnesio-Wüstites.

The solid solutions between MgO and FeO are readily prepared by careful grinding together of Fe_2O_3, Fe powder, and MgO in the appropriate amounts to give the desired composition. The mixture is heated in a sealed, evacuated silica-glass tube at about 1200° for 48 hours. Fusion must be avoided and reaction permitted to occur between the solids. A thin skin of silicate forms at the contact of the preparation with the tube, but the main mass consists of minute crystals of a solid solution of MgO and FeO. These show a continuous variation of properties with composition. In color they vary, as powder, from pure white at the MgO (periclase) end, through pale yellow and brown to a black, opaque material at the FeO end. Even at 90 wt. per cent FeO a certain amount of brownish light is transmitted by very small crystals under the microscope. As far over as 78 per cent FeO enough light is transmitted to permit measurement of the refractive index in immersion media under the microscope, though the measurements are not of high accuracy in the iron-rich varieties. The results for sodium light are given in Table IV and Fig. 24.[22] It will be noted that when the composition is plotted in mol per cent the variation of refractive index is linear within the limit of error of measurement. Extrapolation suggests a value of 2.32 for the refractive index of FeO.

---

[22] We are indebted to Dr. H. E. Merwin for special immersion media of high refraction and for guidance in their use.

TABLE IV.

Refractive Indices of Magnesio-Wüstites.

Composition				
wt. per cent		mol per cent		
MgO	FeO	MgO	FeO	Refractive index
100	..	100	..	1.736 ± .002
90	10	94.1	5.9	1.768 ± .002
75	25	84.3	15.7	1.822 ± .003
50	50	64.2	35.8	1.948 ± .005
21.9	78.1	33.3	66.7	2.12 ± .01

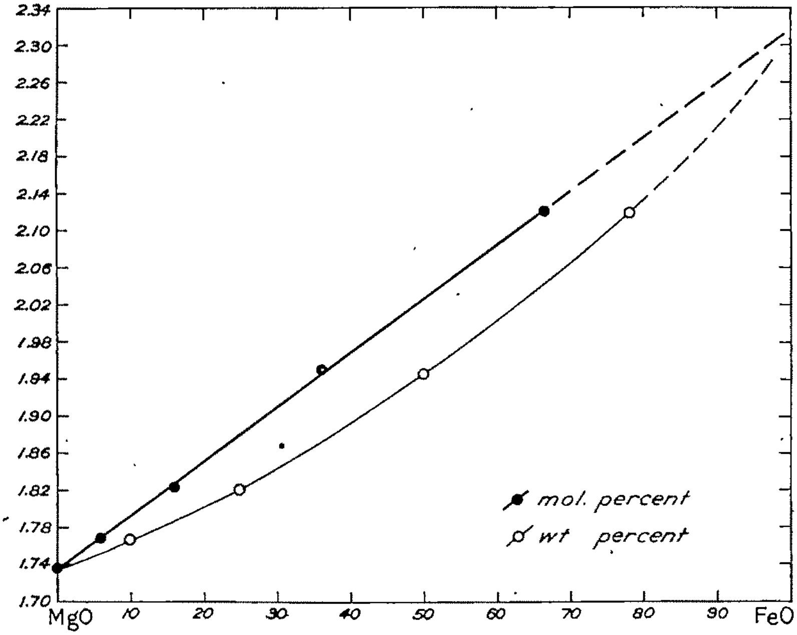


Fig. 24. Refractive indices of magnesio-wüstites.

Olivines.

Pure Mg-Fe olivines free from ferric iron and other oxides can be prepared by baking together for 48 hours MgO, Fe, Fe_2O_3, and SiO_2 in the proper proportions for the desired composition. This is accomplished in the absence of oxygen by sealing the mixed powders in an evacuated silica tube. Again fusion must be avoided and the reaction permitted to proceed between solids. The crystals of olivine prepared in this manner are rather minute but their refractive indices can be measured in immersion liquids under the microscope with considerable accuracy. The manner of variation of the refractive indices with composition in olivines has been the subject of a number of investigations. The natural minerals used, though permitting high accuracy of measurement, leave something to be desired because they contain small amounts of a number of different oxides whose individual effects are not readily made out. It is now 25 years since Backlund suggested that if the composition is plotted in molecular proportions the variation of refractive indices in Mg-Fe olivines is linear.[28] Natural olivines have not been of sufficient purity to permit the definite establishment of this relation but the synthetic olivines here prepared show that the relation is strictly true within the limit of error of measurement on the small crystals obtained. It is possible, of course, that some deviation from the linear relation could be made out if synthetic crystals large enough for plates and prisms were available. The results of the present measurements are given in Table V and in Fig. 25.

TABLE V.

Optical Properties of Synthetic Mg-Fe Olivines.

Composition						
wt. per cent		mol per cent		refractive indices		
Mg_2SiO_4	Fe_2SiO_4	Mg_2SiO_4	Fe_2SiO_4	γ	β	α
100	..	100	..	1.6688	1.6507	1.6359
75	25	81.3	18.7	1.709	....	1.671
50	50	59.2	40.8	1.752	1.738	1.712
25	75	32.6	67.4	1.807	1.794	1.762
10	90	13.9	86.1	1.848	1.835	1.798
..	100	..	100	1.875	1.864	1.824

---

[28] Backlund, Helge: Travaux du Musée Geologique Pierre le Grand, St. Pétersbourg Tome III, 77-105, 1909.

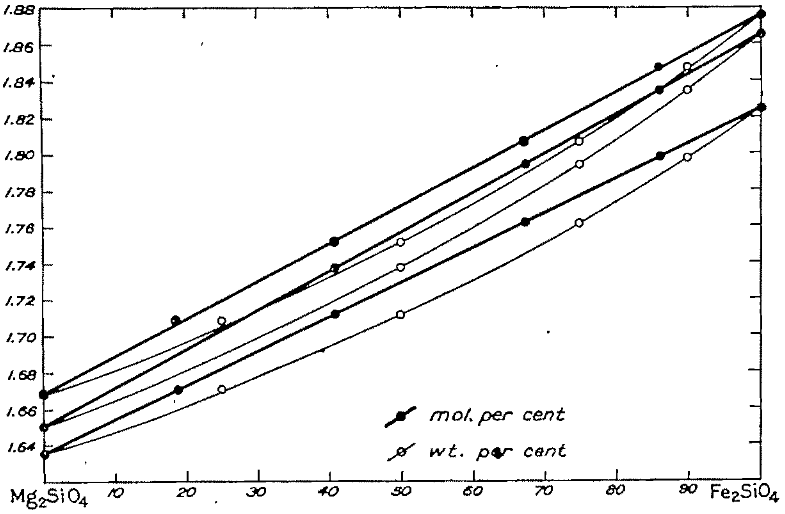


Fig. 25. Refractive indices of Mg-Fe olivines.

Pyroxenes.

Members of the $MgSiO_3$-$FeSiO_3$ series of pyroxenes were prepared in the present work in a form suitable for measurement of their refractive indices by devitrifying glasses of metasilicate composition. This procedure gave only clino-pyroxenes and although we occasionally obtained crystals of ortho-pyroxenes in our studies upon the transformation temperature, they were not suitable for the fixing of the variation of optical properties with composition in the orthorhombic pyroxenes. The clino-pyroxenes form an interesting series which extends over as far as about 87 per cent $FeSiO_3$. Those containing up to 70 per cent $FeSiO_3$ were prepared in the pure form by the method mentioned above. It is not possible to get homogeneous glasses richer in $FeSiO_3$, so beyond this point no pure synthetic clino-pyroxenes were made. It is possible, however, to prepare clino-pyroxenes of known composition from natural ortho-pyroxenes of known composition by simple inversion. This method was used in preparing the one clino-pyroxene with more than 70 per cent $FeSiO_3$. It was obtained by inversion of the Tunaberg ortho-pyroxene and of course contained all the extraneous oxides of the original mineral.

The clino-pyroxenes of the present series are all polysynthetically twinned on 100. They all have a small optic axial angle of about 20-25° positive and the plane of the optic axes is ⊥010. The extinction angle $c_\wedge\gamma$ rises from 22° in pure $MgSiO_3$ to 42° in the 60 per cent $FeSiO_3$ member and then falls off again to 36° in the extreme solid solution. The rise is so rapid with initial additions of $FeSiO_3$ that it was, at first, supposed that the extinction passed through 45° and that the smaller angles measured were complementary to $c_\wedge\gamma$, but careful work showed that this was not true and the passage of the extinction through a maximum was definitely established (see Fig. 26).[24]

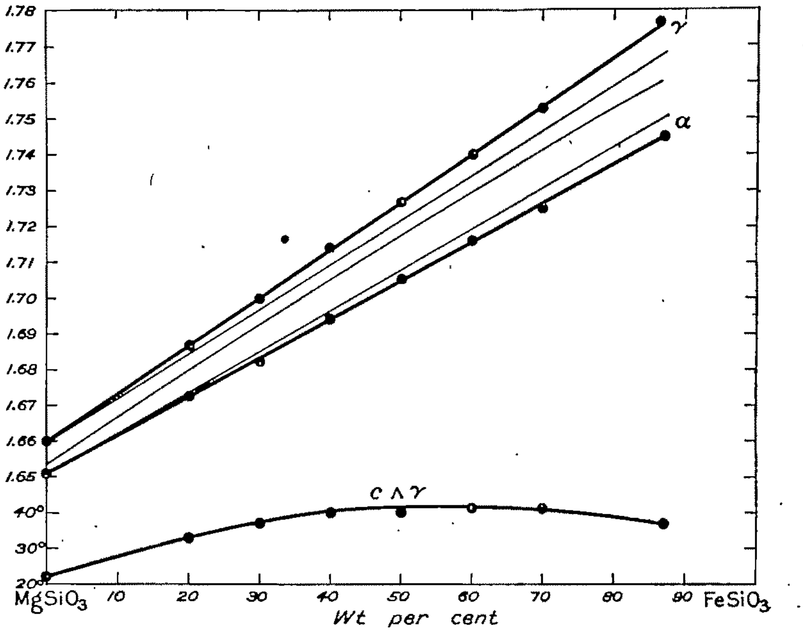


Fig. 26. *Heavy curves.* Refractive indices, γ and α, and extinction angles of monoclinic Mg-Fe pyroxenes. The curve for β is omitted because it lies very close to and nearly parallel to the curve for α. *Light curves.* Most probable values of the refractive indices, γ, β and α, of the orthorhombic Mg-Fe pyroxenes.

---

[24] Certain natural bronzites with obscure twin bands showing low extinction angles are discussed briefly on p. 169. It may be added that one of us (B) has noted that an obscure polysynthetic twinning, with low extinction angles of the bands, is prevalent in the olivine of ultrabasic rocks as well as in orthorhombic pyroxene.

If the composition is plotted in weight per cent the variation of the refractive indices, within the error of measurement, is linear. In Fig. 26 only γ and α are plotted; the curve for β would be practically parallel to that for α and very close to it. For comparison the figure shows curves of the three refractive indices of orthorhombic pyroxenes as light lines, the values used being those from the literature that appear to be the most reliable and significant determinations upon natural minerals. The much higher birefringence of the clino-pyroxenes except at the $MgSiO_3$ end is clearly brought out.

The optical properties of the Mg-Fe clino-pyroxenes are summarized in Table VI.

TABLE VI.

Optical Properties of Synthetic Mg-Fe Clino-pyroxenes.

Composition wt. per cent		Refractive indices		Extinction angle	Optic axial angle and orientation
$MgSiO_3$	$FeSiO_3$	γ	α	$c \wedge \gamma$	
100	0	1.660	1.651	22°	All have a small + optic axial angle of some 20°-25° and plane of optic axes ⊥ 010
80	20	1.687	1.673	33	
70	30	1.700	1.682	37	
60	40	1.714	1.694	40	
50	50	1.727	1.705	40	
40	60	1.740	1.716	42	
30	70	1.752	1.725	42	
13	87*	1.777	1.743	36	

* This clino-pyroxene was prepared by inverting a natural ortho-pyroxene from Tunaberg, Sweden, which contains 42.23 per cent FeO and 3.88 per cent MnO.

Glasses.

Only a limited range of compositions in the system can be quenched to a glass. Examination of Fig. 27 shows clearly what range is covered. In that figure all the mixtures that were quenched to glass are plotted and the determined refractive indices are indicated by isofracts or curves of equal index, the numerical values being given in Table I. The area which embraces the determined points lies in a general way along the trough between the olivine field on the one hand and the silica (cristobalite-tridymite) fields on the other, a trough partly occupied by the pyroxene field (Figs. 5 and 6).

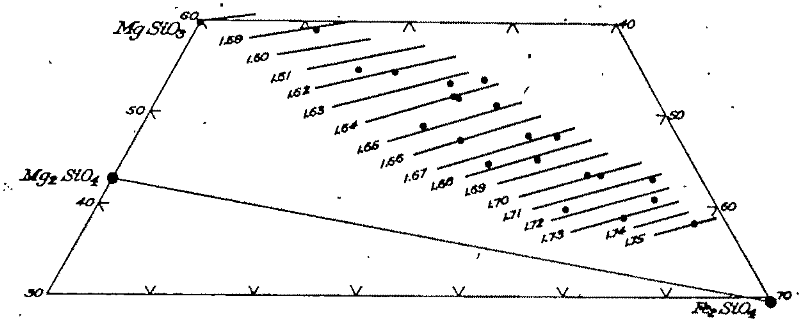


Fig. 27. Refractive indices of glasses.

BEARING OF THE RESULTS UPON PETROLOGIC PROBLEMS.

The pyroxenes and the olivines are among the most important of rock-forming minerals. The natural minerals, particularly the pyroxenes, are of more complex character than the simple members here studied, and especially are formed from more complex liquids than those of the present system. Nevertheless, some of the equilibrium relations here found are of general significance in rock problems and are a necessary step in the solution of the broader problem.

Pyroxenes and their Equilibrium Relations.

The monoclinic pyroxenes of the $MgSiO_3$-$FeSiO_3$ series are but little known to the petrologist, the clino-enstatite of meteorites being the most familiar representative among natural products. The controlling factor is no doubt the same as that determining the absence in nature of pseudowollastonite, carnegieite, and many other crystalline silicates familiar to laboratory workers. They are high-temperature forms and are represented by their low-temperature equivalents, usually because the natural solutions and melts crystallize only at low temperatures. When Mg-Fe metasilicate crystallizes from magmas it almost invariably assumes the orthorhombic form, stable at temperatures below 1140° at the magnesian end and below 955° at the other extreme. It is safe to conclude, therefore, that the crystallization of orthorhombic pyroxene took place below the temperatures mentioned, and since orthorhombic pyroxene is one of the earliest of minerals in those rocks in which it occurs, the indications of low-temperature crystallization of these rocks are clear. Moreover, the change of volume involved in the inversion is so small (as suggested by the near identity of mean refractive index) that the effect of pressure will be negligible. The conclusion reached as to the maximum temperature of crystallization of orthorhombic pyroxene will hold for any depth.

There is already a great body of evidence pointing to the crystallization of the more complex rocks at moderate temperatures, so the facts just pointed out represent merely further confirmation of opinions widely held. There are, however, rocks of especially simple constitution whose conditions of formation are a matter of debate. Among these are rocks made up almost exclusively of orthorhombic pyroxene. Some petrologists favor the opinion that these rocks crystallized directly from a melt of their own composition. The present study shows conclusively that such crystallization would take place at temperatures far above those at which orthorhombic pyroxenes would form. It seems clear, too, that the orthopyroxenes of these rocks were orthorhombic from the beginning and are not the product of inversion from the high-temperature monoclinic form. In a sufficient number of such rocks ortho-pyroxene exhibits the outward form appropriate to orthorhombic symmetry.

The alternative then naturally suggests itself that the rocks under consideration did indeed crystallize from magmas of approximately their present composition but containing volatile constituents that lowered the temperature of crystallization and were lost during that process. But when we consider the fact that a temperature-lowering of some 300° would probably be required (the interval between the liquidus and the inversion curve is upwards of 400° in the pure minerals, see Fig. 8), we may reasonably doubt whether the necessary quantity of volatiles could have been present and yet leave no evidence of their presence in the formation of hydrous phases such as amphibole, which are often entirely lacking.

The alternative to which we seem to be driven is the concept that most rocks made up of orthorhombic pyroxene were formed as the result of local accumulation of crystals of one kind from a magma of complex constitution, crystallizing at the low temperature appropriate to such constitution.

The orthorhombic pyroxenes of the rocks just discussed are always highly magnesian, a fact in keeping with their presumed origin as accumulated early crystals. Iron-rich ortho-pyroxenes have a totally different origin. They occur in cavities of lavas where they are formed by solutions or vapors, or again in such rocks as eulysite where the intervention of mineralizing solutions is highly probable. As compared with truly magmatic minerals they belong to a relatively low temperature phase of activity and it is not surprising that they assume the orthorhombic form.

Although one can reach the definite conclusion that orthorhombic pyroxene did not form at high temperature, the converse does not necessarily follow. It is not safe to assume that the monoclinic modification of the Mg-Fe pyroxenes must form only at high temperatures. It is a common observation that crystalline phases stable only at high temperatures may form metastably at low temperatures especially if rapidly formed, and in this respect clino-pyroxenes of the present series are no exception. Among rock minerals there are no clino-pyroxenes belonging strictly to this series, but the pyroxenes low in CaO known as pigeonite approach it rather closely.[25] An interesting example of these is the "uniaxial augite" from Mull described by Hallimond.[26] Minor constituents aside, its composition may be expressed approximately as $MgSiO_3$ 35 per cent, $FeSiO_3$ 56 per cent, $CaSiO_3$ 9 per cent by weight. In optical properties it shows a close approach to a pyroxene of the pure Mg-Fe clino-series having $MgSiO_3$ 40 per cent, $FeSiO_3$ 60 per cent. There can be little doubt that the stable condition of the substance of this uniaxial augite at low temperatures would be an orthorhombic pyroxene with a small admixture of lime-rich monoclinic pyroxene, and the suggestion is that these crystals formed at a high temperature. Unfortunately, this cannot be regarded as established, for, as we have seen in the foregoing, they could presumably form metastably at a temperature below the range of their stable existence. The inversion temperature of their closest relative in the pure $MgSiO_3$-$FeSiO_3$ series is about 1050°. Their inversion or unmixing temperature would be somewhat lower, but even so it is not probable that these crystals formed above that temperature.

The same remarks may be made with reasonable assurance of most pigeonites. They are probably formed metastably at temperatures below their stability range. In those examples where they occur as phenocrysts it is possible that they were stable crystals, but in the great majority of occurrences as part of the general fabric of basaltic rocks they were probably formed metastably during rapid crystallization. The stable arrangement resulting from very slow, equilibrium crystallization, at the same temperature, would be a mixture of orthorhombic pyroxene and highly calcic clino-pyroxene.

---

[25] The clino-enstatite crystals with rims of enstatite described by Holmes and Harwood should here be noted. They are in the normal relation to be expected with falling temperature. Quart. Jour. Geol. Soc. London, **88**, 404, 1932.

[26] Hallimond, A. F.: Min. Mag., **17**, 97-99, 1914.

These conclusions, strongly indicated by experimental results, are supported by the actual relations in some rocks. Thus Tsuboi finds that the phenocrysts of Japanese andesitic and basaltic rocks, representing slow intratelluric crystallization, are of "both monoclinic and rhombic pyroxenes."[27] On the other hand, the groundmass pyroxenes, representing rapid crystallization, "are, with rare exceptions . . ., all pigeonitic"[28] but in the rare cases where rhombic pyroxenes are found along with monoclinic in the groundmass, the groundmass tends to be high in crystallinity.[29] In other words, if the ordinarily rapid crystallization of the groundmass is sufficiently slowed down, the stable configuration, consisting of the two different types of pyroxene, is reached as definitely there as it is in the porphyritic elements.[30]

Olivines and Olivine-rich Rocks.

Among the most interesting of rocks are those consisting entirely or almost entirely of a single mineral. Their very simplicity presents a problem of the utmost difficulty. Prominent among these monomineralic rocks are the ultrabasic types made up entirely of pyroxene or of olivine. We have already discussed the origin of rock masses consisting of orthorhombic pyroxene and concluded that the evidence appears to favor the concept that they were not formed by simple crystallization of a melt of their own composition but rather by accumulation of crystals from a complex magma. The same concept has been advanced elsewhere as a probable mode of origin of ultrabasic rocks in general, olivine rocks, including dunites, being especially emphasized.[31] It has met with rather wide acceptance, but some adherents believe that, as olivine crystals accumulate (usually by sinking) they are resorbed or remelted, that thus liquids very rich in the materials of the accumulating crystals are produced, and that from such liquids monomineralic and closely related rocks are formed by simple crystallization.

---

[27] Tsuboi, S.: Jap. Jour. Geol. Geog., X, p. 68, 1932.

[28] Op. cit., p. 78.

[29] Op. cit., pp. 71-2.

[30] Although the above explanation of pigeonites as a metastable phenomenon seems acceptable for some rocks it probably does not apply generally. The interesting "pseudo-hypersthenes," recently described from North China, and consisting of a mixture of olivine and pigeonite, pseudomorphous after hypersthene (T. Tomita, J. Shanghai Science Inst. I, 1933, 3) indicate that pigeonite may sometimes be formed at lower temperatures than associated orthorhombic pyroxene, unless it should happen that we are, in this instance, dealing with a change effected by rising temperature, a possibility that the formation of olivine suggests. But this possibility seems to be definitely precluded in the Whin Sill type of quartz dolerite to which our attention has been called in this connection by Dr. Frederick Walker. These dolerites may have all three pyroxenes, orthorhombic, pigeonitic, and lime-rich, in the one rock, separated in the order given. Plainly it is necessary to investigate pyroxene compositions of more complex character before a satisfactory general explanation of pigeonites is forthcoming.

Johann Vogt was a leading exponent of this view, and with the courage of his convictions he accepted the high temperatures necessary to the existence of dunitic magma, in so far as the temperatures were then known. He states: "The temperature of the beginning of crystallization must have been . . . for the dunites at least 1500, occasionally even 1550-1600°."[32] Vogt's temperatures were the best estimates then available and were based on an assumed form of the equilibrium diagram of the system, Mg_2SiO_4-Fe_2SiO_4, in which the liquidus fell off precipitately from the known value 1890° at Mg_2SiO_4, with small additions of Fe_2SiO_4. Fig. 7 shows how far this is from the truth. At a composition where Vogt supposed that the melting temperature would be about 1500° (20 per cent Fe_2SiO_4) it is in reality well above 1800°. Many petrologists found even Vogt's temperatures unacceptable. Thus Harker expressed the opinion that no support is to be found for belief in such temperatures at the time of intrusion of dunites, a remark that would apply with greater emphasis to the temperatures now known to be necessary.

It is sometimes assumed that the olivine rocks contained a large proportion of volatile fluxes now lost. Some of them, such as mica peridotites, may very well have done so, but for many examples, including typical dunite, the assumption is wholly gratuitous. Evidence for the abundant presence of volatile constituents is entirely lacking.

---

[31] Bowen. N. L.: This Journal, 14, 89-108, 1927.

[32] Vogt, J. H. L.: Vidensk. Selsk. Skr. I, Mat. Naturw. Kl., 1924, No. 15, p. 97.

We appear to be reduced to the conclusion that dunites are formed by accumulation of crystals, with perhaps some special mode of intrusion of a crystalline mass for those bodies that seem to be independent intrusives. But discussion of such matters is beyond the scope of this paper. We wish merely to emphasize the difficulties in the way of acceptance of dunitic magma unless there is evidence of the very high temperatures that this investigation has shown to be necessary to its existence, or of the abundant presence of volatile fluxes.

Liquid Peridotite Layer in the Earth.

While we are on the subject of dunitic magma it is perhaps desirable to remark upon the problem of a liquid layer of peridotite (related to dunite) within the earth. In this connection the probable density of the liquid olivine and the effect of pressure upon the melting temperature become important. While we have no intention of discussing the merits of the general theory, our data do permit an estimate of the effect of pressure upon the melting point of olivines which may prove of value in the absence of any better information.

The effect of pressure upon the melting point of any substance depends entirely upon the volume change and the heat effect attending fusion. By applying the theory of ideal solutions to the determined equilibrium diagram of the olivines, values are to be obtained for latent heats of melting. By applying the law of Gladstone and Dale connecting the refractive index and the density of silicates, we may, with the aid of some extrapolation, obtain the volume change of olivines on melting. Objections are to be raised to the precise validity of both theories, but the results of carrying through the reasoning are not without some orienting value.

Latent Heat of Fusion of Olivines.

The olivine diagram is of the same form as the plagioclase diagram to which the theory of ideal solutions has been applied. The method of derivation of the equation is not altogether acceptable in these times but the actual equations reached and used are valid, assuming ideality. It is of interest, in any case, to apply them to the experimental results obtained for the olivines. The equations connecting the concentrations, x and x_1, upon the liquidus and solidus, respectively, at any temperature T with the molal latent heats L_1

and L_2 and the absolute melting points T_1 and T_2 of the two components are as follows, R being the gas constant,

$$\ln \frac{1-x}{1-x_1} = \frac{L_1}{R}\left(\frac{1}{T_1}-\frac{1}{T}\right)$$

$$\ln \frac{x}{x_1} = \frac{L_2}{R}\left(\frac{1}{T_2}-\frac{1}{T}\right).$$ [33]

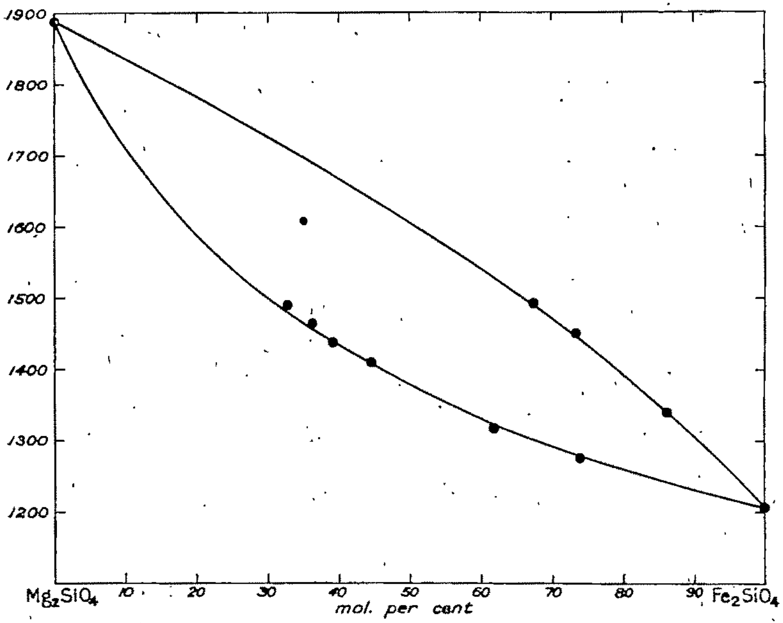


Fig. 28. Calculated solidus and liquidus curves for the system, forsterite-fayalite, using 14000 cal. as molal latent heat of each. Solid circles indicate points determined experimentally.

Preliminary calculations from determined points indicated values approaching 14,000 cal for the molal latent heat of both fayalite and forsterite. The process was then reversed; complete curves were calculated and plotted using the value 14,000 cal for the molal latent heats, and the determined points were then put on the plot. The result is shown in Fig. 28, the curves being the calculated curves and the solid circles the determined points. The deviation of the points from the curves is within the experimental error of determination of the points, the greatest deviation being shown by solidus points which are also those that carry greatest possible error of measurement. The high-temperature portions of the curves lack determined points, except the melting point of forsterite; but with these limitations, and in so far as the theory applied is valid, we may take it that the results indicate molal latent heats of melting of forsterite and fayalite sensibly equal and of a value close to 14,000 cal. This gives in round numbers 69 cal per gram and 100 cal per gram, respectively, for fayalite and forsterite.

---

[33] Bowen, N. L.: This Journal, **35**, 589, 1913.

Volume Change of Olivines upon Melting.

We have made no determinations of the densities of olivines because the materials as prepared do not lend themselves to such determinations, but we have measured their refractive indices. No olivine glasses are available for the measurement of refractive indices because we found it impossible to prepare such glasses, but we have determined refractive indices of many glasses in the system. From these it is possible to obtain indications of the refractive indices of olivine glasses by extrapolation, never wholly satisfactory, but the best means available in this instance. By applying the law of Gladstone and Dale which indicates that $\frac{n-1}{d}$ = constant whether the substance is glass or crystals, we obtain, from the ratio of $n-1$ for the crystals to $n-1$ for the glass, the ratio of the density of glass to the density of crystals. The refractive indices of olivine glasses have been obtained by extrapolating the isofracts of Fig. 27 until they intersect the Mg_2SiO_4-Fe_2SiO_4 join.

In Table VII the results of these operations are given. It is there seen that the change of volume of olivines upon melt-

TABLE VII.

Change of Volume of Olivines upon Melting as Indicated by Change of Refractive Index.

Composition weight Mg_2SiO_4	Fe_2SiO_4	Refractive index of glass (Extrap.) $n$gl	Mean refractive index of crystals $n$xl	$\frac{(n\text{xl}-1)}{(n\text{gl}-1)} = \frac{v\text{gl}}{v\text{xl}}$
100	0	1.634	1.652	1.028
75	25	1.667	1.687	1.029
50	50	1.714	1.734	1.027
40	60	1.732	1.754	1.030

ing suggested by change of refractive index measured at room temperature is about 3 per cent. The method applies only over to about 60 per cent Fe_2SiO_4 because, for the mixtures richer in iron, there are not enough points to determine the direction of the isofracts. Within the determined range there is no adequate evidence of systematic variation. Even if the isofracts, sensibly straight in the determined portion, acquired a curvature, in the extrapolated portion, as great as that exhibited in the CaO-FeO-SiO_2 system,[84] the indicated volume change would be only about 4 per cent.

Effect of Pressure upon the Melting Point of Olivines.

With the small change of volume upon melting suggested by these considerations the effect of pressure upon the melting point of olivine will be correspondingly small. We may calculate the effect of pressure from the volume change and the heat effect with the aid of the Clausius-Clapeyron equation

$$\frac{dT}{dp} = \frac{\Delta V}{\Delta H} T.$$

The density of forsterite is 3.223[85] and $\Delta V = 0.0093$ cm^3 per gram, and the heat effect ΔH is 100 cal per gram, whence $\frac{dT}{dp} = 0.0047$ degrees per atmosphere. A pressure of 1000 atmospheres should therefore raise the melting point of forsterite 4.7°.

Our determinations enable us to estimate the volume change of olivines, upon melting, only about half way over to fayalite, where it still appears to be only 3 per cent. If the same value applied to fayalite, a pressure of 1,000 atmospheres, would raise the melting point only about 3.5°, whereas Goranson[86] has recently found by direct measurement a raising of approximately twice that much. A rapid increase (doubling) of the volume change toward the fayalite end is suggested or, not impossibly, our estimate for the magnesium members may be off 100 per cent, based as it is upon figures obtained by such indirect methods. In any case the volume change of olivines upon melting is considerably less than that occurring with most rock-forming silicates and is probably very small in the more magnesian members which have the greater importance to the petrologist.

---

[84] Bowen, N. L., Schairer, J. F., and Posnjak, E.: Op. cit., Fig. 31, p. 264.

[85] Aurousseau, M., and Merwin, H. E.: Am. Min., 13, 563, 1928.

[86] Personal communication.

Fractional Crystallization.

The fractional crystallization of liquids of the system, MgO-FeO-SiO_2, is remarkable in the possible scope of its results, yet at the same time of rather simple character. In these respects it is not unlike the same process in liquids of the plagioclase system, anorthite-albite. Just as in this latter system the composition albite is the goal towards which all liquids strive during fractional crystallization, so in the present system all liquids strive to reach the composition of the point *M* (Fig. 22).[37] In detail the process is, of course, much more complicated than in the simple binary system of the plagioclases.

Some liquids of the system begin to crystallize with separation of highly magnesian olivine and reach the boundary curve *KL* at a point between *K* and *O* (again Fig. 22). All of these except those in the triangle *KJO* are liquids having a deficiency of silica below the metasilicate ratio (which we shall refer to as *undersilicated*) but upon encountering the curve *KO* they fail to follow it, as they would in non-fractional crystallization. Instead, they precipitate pyroxene only and cross the pyroxene field, acquiring a notable excess of silica over the metasilicate ratio (oversilicated) and reaching the boundary curve *FGRL* which they follow with separation of pyroxene and free silica (cristobalite or tridymite). If fractionation is limited (reaction between liquid and crystals only moderately restricted) the liquid may become completely exhausted when its composition is represented by some point between *G* and *R*. The final liquid is still oversilicated.

On the other hand, if the fractionation is stronger (reaction between liquid and crystals more restricted), some liquid may remain and continue to change composition along *RL*, thus becoming undersilicated once again. In the ideal case of perfect fractionation (complete lack of reaction between liquid and crystals) the liquid would continue past *L* and follow *LM*, olivine and tridymite now separating, until a final infinitesimal quantity of the liquid reached the composition *M*. The crystalline products of this last example would range all the way from highly magnesian olivine as the earliest crystals, through highly magnesian pyroxene accompanied by silica, then more ferriferous pyroxene accompanied by silica, to highly ferriferous olivine again accompanied by silica.

---

[37] We omit, as being of no importance in the present connection, all liquids of lower silica content than the orthosilicate ratio. It is to be noted also that pure olivine liquids fractionate not towards *M* but towards pure fayalite.

Most oversilicated liquids of the system will encounter and follow the curve *FL* during their fractional crystallization and may eventually proceed along *LM*, if fractionation is adequate, in exactly the same manner as the liquids just discussed. Some few oversilicated liquids first encounter the boundary curve *LM* and then proceed along it.

Those undersilicated liquids that reach the boundary curve *KOL* at points between *O* and *b* do not immediately follow that curve. They pass into the pyroxene field with separation of pyroxene but, never becoming oversilicated, follow a curved course that brings them back again to the boundary curve *KOL* which they then follow towards *L*. They attain *L* and pass on towards *M* if conditions permit an adequate degree of fractionation.

Those undersilicated liquids that reach the boundary curve *KOL* between *b* and *L* follow the curve to *L* during their fractional crystallization and may pass on towards *M* if fractionation is adequate, and, of course, some undersilicated liquids encounter *LM* directly.

The perfect equilibrium (non-fractional) type of crystallization discussed on earlier pages may be a very complex process but, when it is completed, the crystalline product is of simple constitution. At the other extreme the type of crystallization showing maximum fractionation is, in general, not so complex a process; but it is extended through a much wider range of temperatures and yields a crystalline product with a greater number of phases and a wide range of composition of the variable phases (solid solutions). These results grow out of the prevalence of incongruent melting and solid solution in the system. It is this principle of flexibility of crystallization introduced by the phenomena just mentioned that renders the course of crystallization and the products of it responsive to the conditions attending crystallization. The importance of this principle has been pointed out elsewhere,[38] but no apology is here offered for emphasizing it once again especially in connection with experimental results upon such important rock-forming minerals as pyroxenes and olivines.

---

[38] Bowen, N. L.: The reaction principle in petrogenesis, J. Geol., 30, 177-198, 1922.

The fact that the pyroxene series of solid solutions of this system shows the one type of incongruency at one end of the series and the opposite type at the other end is a matter of much interest. The incongruent melting of clino-enstatite with separation of olivine and the consequent throwing of excess silica into the liquid has been made a point of great importance in the theory of the derivation of salic magmas from basaltic magma by fractional crystallization. To some it may seem that, since the addition of 20 per cent of $FeSiO_3$ to clino-enstatite completely neutralizes this tendency, the foundation of the theory is greatly weakened, and this would be true if the whole story were as just stated. Rather is it that the discovery of the incongruent melting of $MgSiO_3$, and its consequences, pointed to an explanation, by appeal to analogy, of the long observed fact that the olivines of certain rocks have suffered resorption, with the development of reaction rims of pyroxenes about them, and that in many basaltic rocks in which this is observed, a highly siliceous, interstitial crystallization-residuum is found. Other explanations of these phenomena had been and still are offered, notable among which is that which appeals to the effects of volatile components, but no one has been able to offer the slightest suggestion of evidence that volatile components could bring about such a result, whereas appeal to analogy with the phenomena observed in experimental studies furnishes something definite and tangible as a basis for our reasoning. Just which compositions of pyroxene and olivine will show the relation necessary to give a residual liquid enriched in silica we cannot know until experimental studies have covered a wider range of compositions. It has been ascertained that the important pyroxene, pure diopside, does not bear the necessary relation to olivine but, on the other hand, a wide range of pigeonite-like pyroxenes between diopside and clino-enstatite do have it.[39] The present investigation shows that those pyroxenes of the $MgSiO_3$-$FeSiO_3$ series containing more than 20 per cent $FeSiO_3$ fail to show the required relation. But even when these studies have been carried forward to include still more complex pyroxenes, it will still be necessary to ascertain the effects of addition of other phases such as feldspar, for these can exert specific effects upon the relation in question. The influence of anorthite upon the melting-relation of clino-enstatite has already been examined[40] and found to more than treble the amount of "excess" olivine that can separate. All of these investigations are to be regarded as a concerted effort to lessen the gap between investigated systems and natural magmas, in order that the facts gleaned from the investigations may be applied with ever-increasing confidence to the interpretation of magmatic phenomena. In the meantime, we must make applications as best we may, realizing that some of the conclusions will inevitably require modification with increased knowledge.

---

[39] Bowen, N. L.: This Journal, 38, 207-264, 1914.

[40] Andersen, O.: This Journal, 39, 407-454, 1915.

An example of such a situation is furnished by our present results. The fact that in liquids of the system, MgO-SiO_2, forsterite, if any forms at all, will necessarily separate before clino-enstatite, has been used to explain the observation that ordinarily in rocks olivine, even when present in very small amount, has evidently separated at a very early stage and especially before pyroxene. This relation may be expected to hold the more rigidly the more our natural olivine and pyroxene approach a highly magnesian composition, but, as the natural olivine and pyroxene depart from this composition, the relation between them will suffer concurrent modification. The present results show that a different relation obtains if the olivine and pyroxene have a high iron content. Thus from all liquids in the area *ORL* of Fig. 22 pyroxene separates first and is followed by olivine, which is then comparatively rich in iron. It is not surprising, therefore, to find that some rocks are exceptions to the general rule in that they show separation of olivine after pyroxene. Thus Backlund and Malmquist describe Greenland basalts that have this character and, appropriately, the olivine contains iron in amounts far beyond that ordinarily present in basaltic olivines.[41]

These exceptions do not render necessary any modification of the general conclusion that the olivines of basalts ordinarily bear a reaction relation to pyroxene and that, in consequence of this, oversilicated late differentiates can be formed. Nevertheless, they do call attention to the fact that this relation does not universally hold and that for certain iron-rich basalts such late differentiates are not to be expected, but rather undersilicated, alkalic types. It is not probable, however, that distinct parental magmas are absolutely essential to the development of these contrasted late differentiates. As has been suggested elsewhere, a certain amount of flexibility in this respect may be introduced by variation in the rate of cooling of one and the same initial magma.[42] The principles involved are illustrated once again in the present system, with residual liquids alternatively undersilicated or oversilicated, depending upon the degree of fractionation in crystallization.

---

[41] Backlund, Helge, and Malmquist, D.: Meddelelser om Gronland, Bd. 87, Nr. 5, p. 45, 1932.

In this connection attention is to be called to the small change of volume of olivine upon melting, as compared with that of pyroxene, because it indicates that at high pressures the pyroxene field will be extended at the expense of the olivine field and the incongruent character of the melting of pyroxene will disappear. How important this may be in a natural magma it is impossible to predict. We have the tendency of $FeSiO_3$ and of high pressure to suppress incongruency and on the other hand the tendency of the anorthite molecule to enhance it, and the state of balance between these and other factors now unknown is not determined by any experimental investigation. Natural rocks do, however, seem to indicate the persistence of the reaction relation of olivine in some magmas at all depths that come under our notice.

Olivines and Pyroxenes of Metamorphic Rocks.

In an igneous rock there is an order of separation of its constituent minerals, and between the period of separation of one mineral and another there is a change of composition of the liquid. At the time of its separation each of two minerals may have been in equilibrium with the liquid as it then existed but frequently they may not be in equilibrium with each other. Thus we are accustomed to find that in igneous rocks containing olivine and pyroxene the olivine is ordinarily more magnesian than the pyroxene. Yet the olivine in equilibrium with a pyroxene, if they approach the composition of those phases in the present system, should be less magnesian than that pyroxene, as shown graphically in the isothermal figures 9-18. Olivine and hypersthene formed simultaneously in a rock, by recrystallization during a metamorphic episode, should be such that the olivine contains less of the forsterite molecule than the hypersthene does of the enstatite molecule. There are probably not enough observations to permit a statement as to how generally this expectation is borne out in such rocks.

---

[42] Bowen, N. L.: The Evolution of the Igneous Rocks. Princeton, 1928, pp. 236-240.

The Quartz Basalts.

The type of incongruent melting, opposite to that with which we have heretofore been concerned, probably has no petrologic importance. This melting with separation of silica, or its converse early separation of silica from the liquid, occurs only with pyroxene very rich in $FeSiO_3$. Such pyroxenes do not appear in rocks formed directly from magmas but are rather the product of low-temperature, metasomatic processes, and the question of their melting relations does not enter.

Those liquids of the system from which olivine and free silica can separate side by side in equilibrium with each other are of interest in connection with the problem of quartz basalts. In these rocks quartz and olivine were present together in a largely liquid magma and the quartz reacted with the liquid, giving pyroxene rims about remnants of the quartz grains. Some investigators have regarded the quartz grains as representing material acquired from extraneous sources.[43] On the other hand, some are of the opinion that the quartz is, like the olivine, a product of early crystallization from the basaltic liquid.[44]

Although free silica and olivine can occur together in equilibrium with liquid and therefore with each other in the present system, this is true only of olivine with 68 or more per cent fayalite. Even this olivine is in equilibrium with free silica at the temperature 1305°. At lower temperatures it reacts with silica and only a still more highly ferriferous variety can then persist in equilibrium with silica. We have determined optically the olivine in a typical specimen of quartz basalt from Rio Grande Canyon, New Mexico, and have found it to have somewhat less than 25 per cent Fe_2SiO_4.[45] There is no support in the present studies for the belief that such an olivine can form in equilibrium with free silica. A word should be said about the possibility that, with increase of pressure, the narrow, wedge-shaped field of the pyroxenes (Fig. 5) would become still narrower and finally disappear, thus bringing into general contact the fields of olivine and of silica. The possibility cannot be categorically denied, perhaps, but indications are strongly against it. A tendency in this direction could occur only if the passing into solution of pyroxene were attended by a much smaller increase of volume than that occurring when olivine and silica passed into solution. Upon this question we may take the changes of volume of the phases upon melting as a reasonably reliable guide. Pyroxenes do show a somewhat smaller change of volume than does silica (as quartz) but, on the other hand, they show, as we have seen, a much larger change than olivines do. It is probable, then, that the pyroxene field of the present system would maintain its width at higher pressures and that the conclusion stated above requires no qualification for such conditions. This is the nearest indication, now obtainable from experiment, as to the possible suppression of the pyroxene field in natural magmas at high pressures.

---

[43] Harker, A.: Natural History of Igneous Rocks, 1909, p. 355.
Finch, R. H., and Anderson, C. A.: Univ. Cal. Bull. Geol., **19**, 245-273, 1930.

[44] Iddings, J. P.: This Journal, **36**, 220, 1888.
Diller, J. S.: U. S. G. S., Bull. 79, 24-30, 1891.

[45] The particular specimen was U. S. G. S. Petrographic Reference Collection No. 548. Finch and Anderson (Op. cit., p. 261) found olivine of nearly the same composition in quartz basalts from Lassen Peak.

TECHNOLOGIC APPLICATIONS.

The contrasted effects of CaO and of MgO upon the melting temperatures of FeO-SiO_2 mixtures are readily brought out by comparison of the two ternary diagrams CaO-FeO-SiO_2[46] and MgO-FeO-SiO_2. The initial effect of the addition of CaO to ferrous silicates is to lower the melting temperatures. The lowest melting mixture of the system (1093°) contains 17 per cent CaO and a wide range of compositions in the neighborhood of this minimum have melting temperatures below 1150°. Such compositions are thus inherently of the nature of slag and it is not surprising that slags of this character are used in non-ferrous metallurgy and, to some extent, in the "acid" processes of iron metallurgy.

On the other hand, from the very beginning, addition of MgO raises the melting temperatures of ferrous silicates, the fundamental cause being the prevalence of solid solution. No mixture with as much as 17 per cent MgO melts below 1400°. For this reason MgO is not ordinarily a desirable addition to such slags. But for the same reason MgO and Mg-rich materials are highly resistant to the fluxing action of the FeO and ferrous silicates contained in slags.[47] Burned magnesite or periclase in the hearth of an open-hearth steel furnace can absorb into itself large quantities of FeO from the metal bath, forming a solid solution with it that does not begin to melt except at a very high temperature (see Fig. 3). Likewise Mg_2SiO_4, or an olivine close to it in composition, formed, say, by the action of a silicate slag on a magnesite refractory or actually used as refractory blocks itself, can absorb as much as 25 per cent Fe_2SiO_4 and yet not suffer beginning of melting at 1600°. Burned lime in the same situation would be notably fluxed, some liquid being formed in the presence of the ferrous silicates of the slags at decidedly low temperatures. It is to be noted, however, that this does not apply with equal force to the CaO present in burned dolomite. The Ca.Fe silicates have lower temperatures of beginning of melting than the Ca.(Mg,Fe) silicates and the periclase of the burned dolomite will thus in some measure prevent too ready fluxing of CaO while, at the same time, introducing its own inherent resistance to fluxing by iron silicates.

---

[46] Bowen, N. L., Schairer, J. F., and Posnjak, E.: This Journal, 26, p. 205, Fig. 6, 1933.

[47] Fisk, H. G., and McCaughey, W. J.: Bull. 70, Engineer. Experiment Station, Ohio State Univ., 1932.

SUMMARY.

In view of the great importance of ferromagnesian silicates as rock-forming minerals a study of equilibrium in the system, MgO-FeO-SiO_2, has been carried out.

No ternary compounds are formed. The system is dominated by three series of solid solutions, the oxide series, MgO-FeO, which is complete, the orthosilicate or olivine series, Mg_2SiO_4-Fe_2SiO_4, likewise complete, and the metasilicate or pyroxene series, $MgSiO_3$-$FeSiO_3$, which is only partial, since $FeSiO_3$ does not exist as such, although solid solutions with nearly 90 per cent of that molecule are formed. The fields of these three mix-crystal series, together with the fields of silica as cristobalite and tridymite, occupy the whole liquidus surface of the triangle (see Fig. 5).

The broader temperature relations are comparatively simple. The magnesian end members of the solid solution series are invariably of higher melting temperature, with the result that the low liquidus temperatures all lie on the FeO-SiO_2 side of the triangle (see Fig. 6). More specifically, the oxide series is of Type I (Roozeboom), the olivine series, of the same type, has a melting temperature of 1890° at the Mg_2SiO_4 end, and of 1205° at the Fe_2SiO_4 end (see Fig. 7). The pyroxene series is much more complicated, by reason of the fact that

at the magnesian end incongruent melting occurs, with separation of olivine, while at the other extreme incongruent melting with separation of silica prevails, and in connection with this latter phenomenon, the pyroxene field wedges out entirely at 1305°, below which temperature olivine and tridymite fields are in juxtaposition (see Fig. 6).

The relations of the metasilicates are further complicated by the fact that they form two mix-crystal series, the monoclinic stable at high temperatures, and the orthorhombic stable at low temperatures. The inversion temperature falls from 1140° at the pure magnesian end-member, to 955° at the iron-rich extreme. A section along the metasilicate join, even although it is not a binary diagram, brings out clearly these characters together with the variant incongruent melting mentioned above (see Fig. 8).

On account of the prevalence of solid solutions and of incongruent melting the courses of crystallization are of particular interest, especially in connection with the potentialities of fractional crystallization. These are discussed in detail, with application to natural magmas.

The simple character of the olivine diagram renders it possible to calculate, under certain assumptions, the latent heats of melting of olivines. The value indicated is 14,000 cal per mol for both forsterite and fayalite, from which 100 cal per gram and 69 cal per gram respectively are obtained. An estimate based on refractive-index measurements has been made of the change of volume of the more magnesian olivines upon melting, the value 3 per cent being indicated, and with these two factors as a basis the change of melting-point of forsterite with pressure is calculated as 4.7° per 1000 atm.

The optical properties of the several phases have been determined and are presented in tabular and graphic forms (see Tables IV-VI and Figs. 24-27).

Brief mention is made of the application of the results to slags and refractories.

Geophysical Laboratory,
Carnegie Institution of Washington.
October, 1934.

SCIENTIFIC INTELLIGENCE.

PHYSICS.

The Thermodynamics of Electrical Phenomena in Metals; by P. W. BRIDGMAN. Pp. vii, 200; 33 figs. New York, 1934 (The Macmillan Company, $3.75).—This volume includes in more condensed and coördinated form, with some revision and extension, the material published by the author on this subject during the past ten years. The laws of thermodynamics possess a generality and a rigor not found elsewhere in science, and so provide a most important type of analysis which is too apt to be forgotten or overlooked in the more exciting recent developments in the field of metallic phenomena. Professor Bridgman, as an outstanding authority on thermodynamics and as an experienced and skillful experimenter on metallic phenomena, has done a great service in thus making his ideas more available. With his usual clarity and insight he begins by defining and analyzing the fundamental concepts involved in the subject. This paves the way for extended discussion of thermoelectric and thermionic phenomena, the Volta effect, effect of surface charge and galvanomagnetic and thermomagnetic phenomena. The two final chapters concern the bearing of the foregoing principles on the electron theory of metals and a brief discussion of change of state, together with a few miscellaneous observations on temperature and pressure effects. The analysis of fundamentals and the discussions of the Volta effect, thermoelectric and thermionic phenomena are especially admirable. With characteristic logic the author stresses the importance of the thermodynamical point of view in avoiding a too ready acceptance of possible mechanisms. Just because a certain postulated mechanism or model, often devised by reasoning from analogy, is successful in accounting for an observed fact is no proof that the model is the true explanation nor does it follow that the model, however successful, is the only one that may be devised. A distinction well brought out is that between observed experimental facts and "constructions" based upon such facts, which latter too frequently reach by a rationalization process the status of observed facts. The book is valuable not only in clarifying widely-held misconceptions but also in stimulating ideas for investigation. A. T. W.

The National Physical Laboratory—Report for the Year 1933. Pp. iv, 284; 50 figs. (including 10 pls.). London, 1934 (H. M. Stationery Office, 13 s.).—Though the general condition of industry throughout the year 1933 has still continued to affect the activities of the National Laboratory by a small demand for industrial testing and investigation, a significant change for the better was noted toward the end of the year. In spite of the handicaps of the times the Laboratory has achieved important progress in many directions.

The Metrology Department has submitted to the Royal Society the results of its work for some years past on the determination of the yard and the meter in terms of the red radiation of cadmium both in dry carbon dioxide and in a vacuum. Further work on standardization has included progress in connection with frequency measurements, the international temperature scale, electrical units and photometry.

The Physics Department has continued its investigation of the thermal and electrical conductivity of metals at high temperatures, notably of iron. A study of optimum conditions for commercial refrigeration systems has shown interesting developments. In the Radiology Division the study of structural changes has been pursued by X-ray diffraction methods, and attention has been given to the study of X-ray dosage and hospital technique.

The new Acoustics Laboratory is in active operation and undertaking a large volume of work, and the Optics Division in connection with its program is developing a differential colorimeter and a photoelectric spectrophotometer.

The Electricity Department, in addition to its work on fundamental units, has improved the technique of alternating bridge methods, has conducted studies of the magnetic properties of alloys, and has studied the capacitance of screen-grid valves. Researches of an electrotechnical character include accurate measuring methods of alternating current and power involving currents up to 20,000 amperes, and the production and study of high voltages up to one million volts.

A Radio Department has been formed, which has taken over the Radio Research Station at Slough with excellent facilities for work. The program involves radio-telegraphic exploration of the ionosphere and direction finding, as well as the development of radio apparatus and methods.

The Engineering Department and Metallurgy Department have continued a large number of technical problems on properties of metals and alloys, fatigue effects, etc. Two modern open-jet wind tunnels and a high-speed tunnel are under construction for the Aerodynamics Department, the latter to produce air speeds nearly reaching the velocity of sound. Theoretical and practical studies have proceeded on such problems as stability and control of aircraft and airscrew flutter. The equipment of the new tank in the William Froude Laboratory is being increased and research has been completed on the wind resistance of ships. Study is also being made on rudder and screw design.

Details on all these subjects are presented in the Report in its usual clear and interesting manner. A. T. W.

GEOLOGY.

Glacial Deposits Outside the Wisconsin Terminal Moraine in Pennsylvania; by FRANK LEVERETT. Pennsylvania Topographic and Geologic Survey, Bull. G7, 1934. Pp. vi, 123, with figs. and map.—This detailed report contains the results of three seasons' field work, mainly supplementing the mapping of the Wisconsin drift border by Carvill Lewis in 1884. The pre-Wisconsin glacial deposits are subdivided into Illinoian and pre-Illinoian. Separation of pre-Illinoian, Illinoian, and Wisconsin deposits is made on a basis of extent of weathering, degree of erosional modification, and in places, areal and vertical position. Weathering of the Illinoian drift is sufficient to have destroyed limestone pebbles and to have reduced many crystalline pebbles to an advanced state of decay, whereas the Wisconsin drift is fresh. Where thick enough to have its own topographic expression, the Illinoian drift still exhibits sag-and-swell topography with closed depressions, but these are subdued compared with the more striking surface forms on the Wisconsin drift.

The pre-Illinoian drift is thoroughly dissected so that all constructional forms have been destroyed. The till is deeply weathered, and the contained pebbles commonly have thick weathered rinds and etched surfaces. The pre-Illinoian drift of eastern Pennsylvania is regarded as equivalent to the Jerseyan drift of New Jersey. It is very thin and patchy and in some places is a stony clay whose glacial origin is not clearly indicated. No stratified drift is reported in association with it. Several bodies of early glacial gravel in the valleys of northwestern Pennsylvania are described, but no correlation with deposits farther east is attempted.

The Illinoian valley train in the Susquehanna Valley is rather tentatively correlated with the Wicomico terrace at the mouth of the Susquehanna, on the dual basis of (1) partial similarity in lithology and (2) comparable degree of erosional dissection.

Southeast of the Appalachian ridges, the Illinoian drift border is marked by a definite end moraine, but elsewhere this drift generally feathers out in patches. The larger valleys contain a good deal of stratified drift, including extensive valley trains. The author finds this drift border very much more lobate than was formerly believed, indicating former ice tongues in the valleys, separated by ice-free ridges.

The report contains an interesting history of Pleistocene studies in Pennsylvania, beginning with the work of J. P. Lesley in 1850.

R. F. F.

Outline of Physical Geology; by CHESTER R. LONGWELL, ADOLPH KNOPF, and RICHARD F. FLINT. Pp. v, 356; 297 figs. and frontispiece. New York, 1934 (John Wiley & Sons, $3.00).—This is an abridged edition of the "Textbook of Geology," by the same authors (1932). The subject matter and method of presentation are essentially the same, the chief difference is in the length (356 *vs.* 514 pp.). The treatment here is properly less comprehensive, somewhat simpler, and less technical. The authors have thus succeeded in their difficult task of reducing the larger textbook to one of lesser length.

In general, the standard arrangement for most textbooks in physical geology is followed. The gradational processes are treated first: including weathering, streams and valleys, sub-surface water, lakes and swamps, glaciation, wind, and sea. Sedimentary and igneous rocks, with volcanoes, are treated next, followed by diastrophism and earthquakes. The last four chapters discuss metamorphism, structure and history of mountains, land forms, and mineral resources. There are two appendices, one treating of minerals, a second of topographic maps.

Many of the photographs are refreshingly new and the authors have made particularly skillful use of aerial photographs. Among the ones deserving mention are: those of Mt. St. Helens and Mt. Adams (frontispiece); a stream of molten lava (fig. 3), stream erosion (figs. 24, 26), glacial features (figs. 72, 82, 85, 93, and 110), marine features (figs. 124, 133), Halemaumau (fig. 167), and others.

There are also many excellent block diagrams, and, particularly noteworthy, are those illustrating the evolution of land forms and geologic structures; erosion under a humid climate (figs. 45-50); erosion under an arid climate (figs. 56-60); cycle of valley glaciation (figs. 97-100); shoreline of submergence (figs. 133-137), and shoreline of emergence (figs. 138-142).

The book, as a whole, is well written and so presented that it should be comprehensible to even the most elementary student. Most terms are clearly, concisely, and accurately defined. Moreover, the book is entirely up-to-date in its outlook and throughout invariably expresses modern concepts on geologic problems. It is not merely a rehash of old ideas. The analysis of the erosion cycle in semi-arid, and arid regions is a distinct addition to the treatment usually given to the erosion cycle.

Some critical suggestions may be added: The section on land forms, as treated by the authors, belongs in the chapter on streams and valleys. The former deals only with features resulting from stream erosion. Those resulting from glaciation and marine erosion are treated in the chapters on glaciation and the sea, but land forms resulting from stream erosion are placed in a special chapter at the end of the book. The chapter on metamorphism might more easily be associated in such a textbook with the chapters on sedimentary and igneous rocks. Further, the history and origin of mountains might be placed with diastrophism, but the reviewer concedes that there is considerable justification for placing this matter separately. MARLAND BILLINGS.

MISCELLANEOUS SCIENTIFIC INTELLIGENCE.

Chan Kom: A Maya Village; by ROBERT REDFIELD and ALFONSO VILLA R. Carnegie Institution of Washington, Publication No. 448, 1934. Pp. viii, 387; 16 pls., 15 figs., 6 tables.—The research projects of the Carnegie Institution of Washington in the peninsula of Yucatan and the country to the southward cover a wide range of subjects. The archaeological investigations are well known; Dr. Shattuck and his colleagues have given us a most important work on the medical and biological sides. Dr. Redfield and his Maya informant, Alfonso Villa, have now published an intensive study of a Maya village.

This work is the first of three which have been planned as a comparative piece of sociological and ethnological research to cover "first, a community in which the folk culture is fairly complete, and second, the study of other communities where that culture is in disorganization or conversion into something else," and third, investigation of the large Spanish-Maya city of Merida.

Chan Kom is practically a pure Maya community. Its history, tools and techniques, economics, division of labor, the sociology of the family and of the village, the religion and ceremonies, the life of the individual are all treated most exhaustively along modern lines of anthropological research. Dr. Redfield is rightfully little concerned with a dissection of beliefs and practices into those which are pure Maya and are an ancestral inheritance and those which are derived from Spanish contact. He finds "an integrated and unified mode of life, that is neither the aboriginal Indian culture nor that of Spain, but a third thing. It is not the sum of Indian and Spanish elements, but a new development resulting from the contact of diverse cultures." Alfonso Villa gives in an appendix a full diary of his life as a teacher in the Chan Kom school. There is material here for still another study.

This book cannot be recommended too highly, not only for its contents but also for its techniques of modern anthropological research. It is essentially a "case history" of a folk community which should furnish data for sociologists, economists, students of primitive religion, and those interested in the general subject of folk-lore.

ALFRED M. TOZZER.

Ventilation: A Textbook for Students and Engineers; by E. L. JOSELIN with a foreword by J. ROGER PRESTON. Pp. viii, 238; 165 figs., 2 folding pls., 31 tables. London and New York, 1934 (Edw. Arnold & Co., and Longmans, Green & Co., $5.75).—A distinctive feature of this book is its adherence to questions of air, its properties and measurements thereof, its distribution and conditioning to achieve fresh and comfortable conditions. The presentation is simple, direct and clear. It succeeds in its intention of being entirely practical. The thorough treatment of air duct design, flow of air through ducts and fan characteristics should be valuable to many engineers who wish to lay out ventilation systems of the conventional type. A chapter on natural ventilation by an English author is clothed with authority and tradition and should remind American readers of a phase of ventilation that is largely neglected in this country. Engineers should be reminded that English and American standards of comfort are not the same and some care should be exercised in the selection of data. It is believed that the preliminary chapters would be enlightening to laymen who may be interested in the subject of air conditioning.

L. E. SEELEY.

Zur Erforschung des Weltalls, Acht Vorträge über Probleme der Astronomie und Astrophysik: von P. ten Bruggencate, E. F. Freundlich, W. Grotrian, H. Kienle, and A. Kopff. Pp. 286, 25 x 16 cm., 153 figs. Berlin, 1934 (Julius Springer, price 18 Marks; or 19.80 Marks bound).—In recent years and in all the chief languages there has been a marked increase in the number of expositions of astronomy and of physics. There is a good explanation and a good excuse for this output; the progress of these sciences is so rapid that a treatise of five years ago complete at that time would now be sadly out of date in a number of important fields. In such a work on astronomy, for example, there would be little or no mention of the expansion of the universe, the rotation of the galaxy, or of the nature of interstellar absorption. The work before us, by five of the younger leaders of German astronomy is, as we should expect, admirably up-to-date. The titles of the eight chapters (or lectures) indicate how completely the field of sidereal astronomy is covered: The Importance of Astrometrical Methods in Modern Astronomy, The Physical Characteristics of Stars, The Inner Constitution of Stars, The Sun, The Distances and the Distribution of Stars, Kinematic and Dynamic Relations in the Stellar System, Certain Optical Phenomena in the Stellar Universe, and The Development of Stars. These chapters are necessarily short, averaging thirty-five pages; yet each is a full and excellent statement of the present status of the problems with which it deals. Like other books published by Springer the make-up is very pleasing. Unfortunately, likewise in common with many of the other printings of this firm, the price is high, especially for readers who live, in countries no longer on the gold standard.

FRANK SCHLESINGER.

Earth, Radio and the Stars; by H. T. STETSON. 22 x 14 cm. Pp. xvii, 336. New York, 1934 (Whittlesey House, McGraw-Hill, $3.00).—The fields that lie between two sciences are well known to be the most fruitful to the investigator, and they are also the most fascinating to the general reader of science. In the book before us will be found a good deal of astronomy, some physics, and a little geology, meteorology, and chemistry. The author was one of those who showed us that good or bad reception on our radios is partly a cosmic matter and that it depends to a considerable extent upon what is going on in the sun. He has also unearthed a wholly unexpected relation between the position of the moon and terrestrial latitudes, and more recently, in collaboration with A. L. Loomis, he has found a similar relation between the moon and terrestrial longitudes or local time. The discussion of the first of these discoveries leads naturally to a consideration of solar cycles, of the properties of the stratosphere, of the Kennelly-Heaviside layer, and of the mysterious shell or shells that cause radio-echoing with a lag of from three to fifteen seconds after the original signals. The second set of discoveries, relating the moon in a way not yet understood with latitudes and longitudes, leads to a review of the known properties of the interior of the earth and of its outer crust. The author is guilty of a number of minor inaccuracies, and has attempted, not always successfully, to interest both the general reader and the man of science. But the book is an important statement by one of the chief contributors to the subject. The reviewer does not know of any other work that makes so easily accessible this body of new facts touching so many fields.

FRANK SCHLESINGER.

OBITUARIES.

DR. NICHOLAS EDWARD BROWN, the well-known English botanist, died on November 25 at the age of eighty-five. His chief work was in connection with the Kew Herbarium.

DR. ALFRED HANDS COOKE, student of Mollusca and Curator of Zoology at the University of Cambridge, died on November 28 at the age of eighty.

DR. OLIVER PEEBLES JENKINS, professor of physiology and histology at the Leland Stanford University from 1891 to 1916, died recently in his eighty-fifth year.

DR. KARL VON LINDE, professor of thermo-dynamics at the Technical School in Munich, died on November 16 at the age of ninety-two years.

DR. SAMUEL PARSONS MULLIKEN, professor of organic chemistry at the Massachusetts Institute of Technology, died on October 24 at the age of sixty-nine.

AMERICAN JOURNAL OF SCIENCE

MARCH 1935

CALCUTTA UN
Acc. No.
Book No.
LIBRARY

KERATOPHYRES OF EASTERN OREGON AND THE SPILITE PROBLEM.[1]

JAMES GILLULY.

PART I.

ABSTRACT.

The Permian rocks of the Baker quadrangle and adjacent areas of eastern Oregon include considerable thicknesses of keratophyres, quartz keratophyres, spilites and allied pyroclastics, and albite diabases, mildly metamorphosed in part to albite-chlorite schists. They are associated with marine limestones in such a way as to suggest their submarine origin, and have been intruded by several varieties of plutonic rocks, among them albite granite.

Relics of more calcic plagioclases in the now dominantly albitic rocks, the mottling and inclusions of the feldspars, the direct correlation between the amount of chlorite and epidote among the mafic minerals and the proportion of albite in the feldspars, the ophitic texture of the albite diabases, the presence of albite veins and albite-filled vesicles and association with albite granites showing evidence of albitization, all point to the more albitic of the present feldspars being largely of metasomatic origin, especially in the less siliceous members.

The literature of the spilitic rocks is reviewed and the attempt made to evaluate the several theories advanced to explain their peculiarities. The conclusions reached are: that the spilitic rocks are derivatives of normal alkalicalcic magmas; that the oligoclase quartz keratophyres are probably normal magmatic products of a trondhjemitic differentiation series (a series tending toward oligoclase quartz-diorite) whose trend is probably conditioned by the absorption of water either from the wall rocks as postulated by Goldschmidt or by engulfment of wet sediments; that the spilites, albite diabases, and siliceous rocks richest in albite have all been metasomatically enriched in albite; that this enrichment was probably entirely subsequent to their consolidation and brought about either by resurgent water from the wet sediments as suggested by Daly, or by albitic solutions derived by deeper-seated differentiation along trondhjemitic lines. The common association of albite granites and spilitic rocks is explicable by this source of albitizing solutions. All these conclusions are quite consistent with the commonly geosynclinal locus of spilitic rocks, with the sporadic distribution of their mineral facies, and their frequent association with normal basalts. At the same time they suggest that availability of water rather than simply tectonic conditions governed the trend of differentiation. Anomalous local conditions may thus account for the local occurrence of keratophyric rocks in continental environments.

[1] Published by permission of the Director of the U. S. Geological Survey.

AM. JOUR. SC.—FIFTH SERIES, VOL. XXIX, No. 171, MARCH, 1935.

GEOLOGIC SETTING.

The Wallowa and Blue mountains of eastern Oregon expose, in the midst of the Tertiary volcanic field, considerable areas of pre-Tertiary rocks. This pre-Tertiary terrane is composed dominantly of supracrustal rocks of Carboniferous to Triassic ages invaded by large plutonic bodies ranging in composition from gabbro to albite granite. Some of these plutonic rocks (gabbros, hornblende quartz diorites, trondhjemites, and albite granites) are strongly gneissic, but others (biotite quartz diorites) are massive. Their intrusions have been tentatively assigned to two cycles[2] the later of which at least is of Mesozoic, probably post-Jurassic, age. The earlier may be late Permian, Triassic, or even an early phase of the tentatively distinguished second cycle.

In connection with the keratophyres and spilites to be discussed in this paper, only one group of these plutonic rocks seems worthy of more than passing mention. This group, comprising the hornblende quartz diorite, trondhjemite, and albite granite, has been described in some detail and the conclusion reached that it comprises original diorite and quartz diorite of normal magmatic origin which have in part (and, indeed, in considerable volume) been altered by circulating soda-rich hydrothermal solutions to albite granite. The albite granite is regarded as of metasomatic origin.[3] It is possible that there is a genetic relation between these albitic intrusives and the keratophyric volcanics, although the intrusions are definitely younger than the supracrustal rocks and are probably separated from them by an orogenic period. This matter is discussed in a later section of the paper.

The pre-Tertiary supracrustal rocks of this region have been strongly deformed, probably more than once, in pre-Tertiary time. They are now exposed in closely appressed, in part isoclinal, folds of generally easterly trend, but even their larger structural and stratigraphic relations are still but little known. Tertiary (chiefly post-Miocene) deformation by both folding and faulting along northwesterly lines has been much less intense than the pre-Tertiary, although it dominates the present topography of the region.

---

[2] Reed, J. C., and Gilluly, James: Heavy mineral assemblages of some of the plutonic rocks of eastern Oregon: American Min., vol. 17, pp. 201-220, 1932.

Gilluly, James: Geology and ore deposits of the Baker quadrangle, Oregon: U. S. Geol. Survey Bull. in preparation.

[3] Gilluly, James: Replacement origin of the albite granite near Sparta, Oregon: U. S. Geol. Survey Prof. Paper 175-C, pp. 65-81, 1933.

PERMIAN GREENSTONE.

Distribution.—One of the most widespread formations of the pre-Tertiary terrane of northeast Oregon is a series of altered volcanic rocks with minor sedimentary members, which extends in a belt eastward from a point west of the town of North Powder, across the northern parts of the Baker and Pine quadrangles to the Snake River at Homestead, a distance of about 50 miles. Its farther extent east and west is not at present known, nor, indeed, is its outcrop continuous within this region for it is interrupted by igneous intrusions and by overlapping Tertiary rocks for considerable distances. The present paper is based upon studies of the formation within the Baker quadrangle and for a short distance to the east.

Stratigraphy and Structure.—This formation is so strongly deformed and its exposures are so discontinuous that it has so far proved impossible to decipher the details of stratigraphy. Presumably it overlies the argillite, of Carboniferous age, exposed in Elkhorn Ridge, but whether conformably or not is unknown. Neither have its relations to the known Triassic rocks of the region been determined, but the notably greater metamorphism to which it has been subjected suggests that there is an unconformity between them. From poorly preserved fossils contained in the limestones and associated tuffs, the formation is known to be of Permian age.[4]

Most of the formation is composed of quartz keratophyre flows and tuffs, keratophyre flows, meta-andesites, spilites, albite diabases, and keratophyre tuffs. Subordinate constituents are chert, conglomerate, argillite, and limestone. All these subordinate constituents occur in small, commonly lenticular bodies probably due to the shearing out, during orogenesis, of originally more continuous members.

Owing to strong deformation which the rocks have undergone, their thickness is uncertain within wide limits. Across the northern part of the Baker quadrangle the formation forms a belt, approximately 4 miles wide transverse to the strike, in which the dips are nearly vertical. Although it is probable that this great apparent thickness is due to repetition by isoclinal folding, the diverse lithology of the formation would seem to require at least 4,000 feet of stratigraphic thickness.

---

[4] Girty, G. H.: personal communication, cited in full in U. S. Geol. Survey Bull. 830-A, p. 13, 1932.

Petrography.—The dominant rocks of the greenstone are clearly effusive, and their association with fossiliferous sediments renders a submarine origin most probable, although no pillow structures—such as are common in subsiliceous lavas of this environment—have been detected even among the less siliceous members. Amygdaloids are commonly present but not conspicuous. Contacts between flows cannot ordinarily be recognized because of the widespread metamorphism. Most of the formation is highly sheared, with seams of chlorite dividing the rocks into lozenge-shaped blocks, and in places it is difficult to make the rock break on surfaces other than these shears.

The most abundant component of the formation is quartz keratophyre. These rocks are porphyritic, with sporadic rounded phenocrysts of plagioclase and dark quartz ranging between .5 mm. and 1 cm. in size, set in an aphanitic greenish-gray groundmass which varies from porcellanous to microcrystalline.

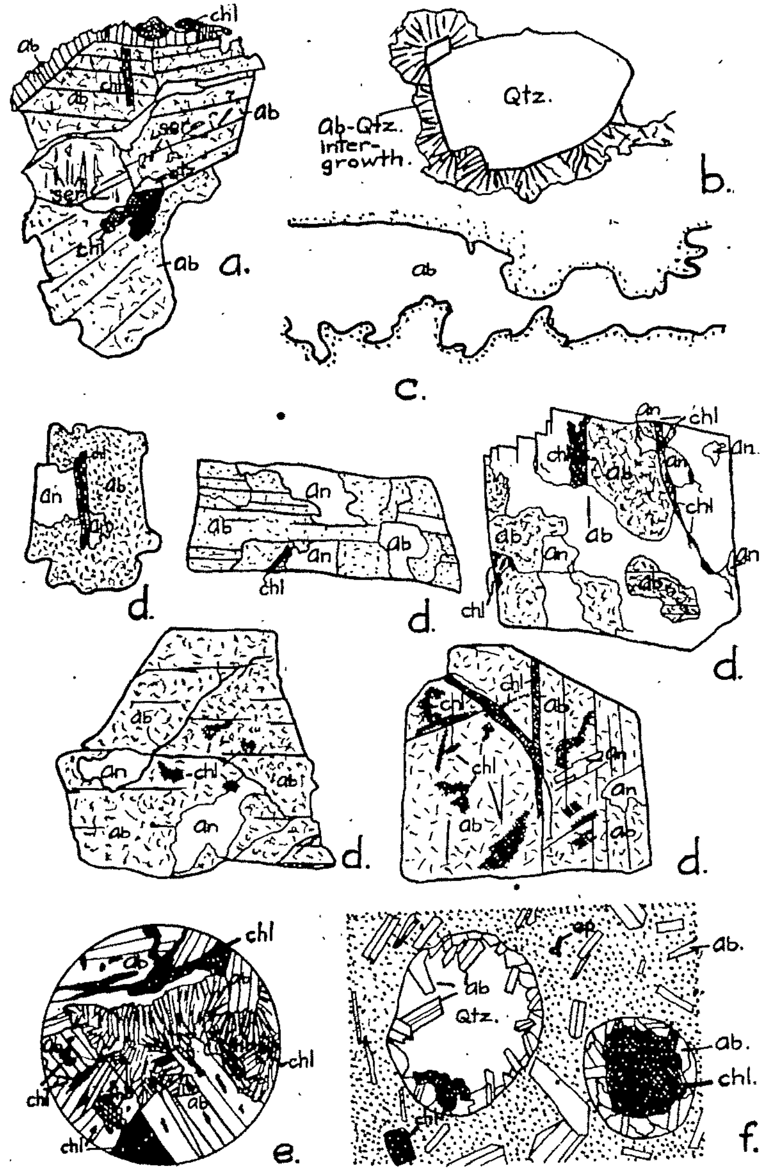
The microscope reveals quartz and cloudy albite set in a groundmass of quartz, albite, and chlorite. Orthoclase may be present in some specimens but was not detected and if present must be in small amount. Epidote, calcite, green hornblende, sericite, and biotite, occur in some specimens and titanite, magnetite, ilmenite, zircon, and apatite are accessory. Chlorite overwhelmingly predominates among the mafic minerals. Groundmass textures range from andesitic (felted) and trachytic through microspherulitic and microfelsitic (devitrified?) to granophyric. The phenocrysts are commonly broken by flow movements in the lava, but orogenic shearing is also evident in practically every thin section. Some of the rocks are wholly mylonitic.

The feldspars range from nearly pure albite to sodic oligoclase. Almost all have γ less than 1.54, corresponding to compositions more sodic than An_5. One analyzed specimen, No. 1 in Table 1, carries only enough CaO to satisfy the P_2O_5 present for apatite. Only one feldspar is apparent in this specimen and since considerable K_2O is present, the albitic feldspar may contain potassium feldspar in solid solution, although symmetrical extinction angles of 16° on sections normal to 010 and angles of 18° to 22° between α and 001 on sections normal to γ correspond to accepted values for nearly pure albite.

Hence, if potassium feldspar is contained in solid solution it does not appreciably affect the optical properties. Some orthoclase is possibly present in the microcrystalline groundmass of this specimen, accounting for the K_2O content, but several other specimens carry much less K_2O so that their feldspars are, except for inclusions, nearly pure Ab. Although some of the feldspars are clear and appear fresh, most are cloudy, owing chiefly to very minute inclusions of chlorite and sericite. Commonly the feldspars are mottled because of the irregular distribution of the inclusions. A few specimens show rims formed by water-clear crystals of albite surrounding and radiating from mottled central crystals of albite. Several specimens have albite with radiate habit surrounding central crystals of either quartz or albite and so intergrown with quartz as to approach the granophyric texture; but it is probable that the texture in these rocks is due not to primary crystallization but to metasomatism, for it is found only in rocks cut by albitic veinlets. These structures are shown in the camera lucida drawings of Fig. 1-a and 1-b, and an albite veinlet with unmatched walls, suggesting a metasomatic origin, is shown in Fig. 1-c. Although the mottled appearance and inclusions in the feldspars suggest a secondary origin, epidote is sparingly present and zoisite practically absent, hence the albite of these rocks is not simply saussuritic, as might be expected from the shearing they have undergone. For these reasons, and because of demonstrable albitization in associated rocks, at least the most albitic of the feldspars are considered as probable products of albitization, although oligoclase, where present, may be primary.

Non-quartzose keratophyres are widespread among the greenstones. Most are finely porphyritic with phenocrysts of plagioclase and, in some, of hornblende, set in a dense, greenish-gray groundmass. Except that they lack quartz the rocks greatly resemble the quartz keratophyres. Locally flow structures can be made out in the field.

Albite (and rarely oligoclase-albite)—commonly of two crystal-sizes—chlorite, epidote, secondary quartz, a little sericite and accessory magnetite, titanite, and apatite, are found in all specimens. The textures are chiefly felted, with some trachytic and felsitic. A few rocks show unaltered augite, but in most this has altered to uralitic amphibole or has been pseudomorphically replaced by chlorite or epidote. Hornblende—pleochroic in green and brown—biotite, clinozoisite,


chl
ab
ab
ser
ab
ser
qtz
chl
ab
a.
Qtz.
ab-Qtz. inter-growth.
b.
ab
c.
chl
an
ab
ab
d.
an
ab
an
ab
chl
d.
an
chl
an
chl
ab
ab
chl
ab
an
an
ab
chl
d.
ab
an
chl
ab
ab
an
d.
chl
chl
ab
chl
an
an
ab
ab
d.
chl
ab
chl
chl
ab
chl
e.
ap
ab.
ab
Qtz.
ab.
chl.
chl
f.

and calcite occur in some specimens. The epidote of these rocks is chiefly a replacement of augite or hornblende, although a minor part replaces the feldspar. Clinozoisite and epidote are contained in the feldspars of some of the rocks, although so little is present that their solution in the feldspar could hardly render the composition more calcic than sodic oligoclase. As in the quartz keratophyres, the feldspars of the non-quartzose keratophyres are cloudy owing to inclusions of chlorite and sericite. Many of the rocks are cut by albitic veins. The evidence that the feldspars are products of albitization of originally more calcic feldspars is much stronger than in the quartz keratophyres, for the textures of these rocks are those of typical andesites, and the partly albitized meta-andesites, next to be described, are found representing intermediate stages in the alteration.

The meta-andesites, although subordinate constituents of the formation, are especially illuminating in respect to the origin of the albitic rocks. They are dark green; some are porphyritic and some non-porphyritic. The phenocrysts—where present—are chiefly feldspar, with less abundant chlorite pseudomorphs after hornblende. The microscope shows felted textures, and the following minerals: labradorite-andesine (in some specimens albite), augite, green hornblende, chlorite, epidote, zoisite, sericite, calcite, secondary quartz, apatite, and ilmenite. Augite and hornblende are invariably partly altered to chlorite and epidote. Some specimens retain quite unaltered feldspars of intermediate composition, others show slight saussuritization, while still others have their original labradorite or andesine embayed and partly replaced by albite which is cloudy from chloritic inclusions and with blebs of chlorite scattered through it. The boundaries of this albite against

---

Fig. 1. Camera lucida drawings of textures and minerals of the Permian greenstone of Eastern Oregon.

a. Cloudy and mottled albite rimmed by radiate clear albite, in quartz keratophyre.

b. Quartz crystal surrounded by radiating intergrowth of quartz and albite, in quartz keratophyre.

c. Albite vein in quartz keratophyre of b.

d. Albite crystals showing mottling by irregularly distributed inclusions of chlorite and sericite and with remnants of original andesine. Keratophyric meta-andesite.

e. Corroded crystals of albite mottled by chlorite inclusions, in meta-andesite.

f. Amygdule in spilite, lined with water-clear albite and filled with quartz; a second amygdule lined with clear albite and filled with chlorite. ab = albite, an = andesine, qtz. = quartz, chl. = chlorite, hb = hornblende, ser. = sericite.

the more calcic feldspar are far too irregular to be referred to zonal growth. In a few specimens this replacement has proceeded to the extent that only cores of the original more calcic feldspars remain, but in others it is incipient or even absent. Representative crystals showing advanced replacement are shown by camera lucida drawing in Fig. 1-d and 1-e.

These features suggest strongly that in the associated keratophyres the feldspars richest in albite are secondary, for the rock textures are identical and the only mineralogic differences between the two varieties are in their feldspar compositions and in the considerably greater ratio of chlorite to pyroxene and amphibole in the keratophyres as contrasted with the meta-andesites. There seems clearly to be a direct correlation between the amount of chlorite and epidote among the mafic minerals and the amount of albite among the feldspars in these rocks.

A few specimens best described as spilite were collected from the formation. Superficially these resemble the dense meta-andesites but the microscopic features: divergent granular textures and chlorite pseudomorphs after olivine, suggest an originally basaltic composition. Hornblende and augite are relatively common in these rocks though chlorite is probably the dominant mafic mineral. The feldspar is albite at least as sodic as An_4, much of it clear but other grains cloudy with epidote and sericite. Some specimens are amygdaloidal, with euhedral water-clear albite crystals lining the former vesicular cavities whose centers are now filled with quartz and chlorite. See Fig. 1-f. These rocks, accordingly, show albite of definitely hydrothermal origin as well as do the meta-andesites.

Albite diabase is a minor component of the greenstone. It is finely crystalline, dark greenish gray and with macroscopic feldspar and chlorite. The microscope reveals an ophitic texture with the original pyroxene altered to uralite and chlorite. The feldspar is albite (An_2—An_4), practically free from zoisite or epidote. Such epidote as occurs in the rock is in the chlorite pseudomorphs after augite, not in the feldspar. Ilmenite, leucoxene, and magnetite are accessory.

A large part of the greenstone series is composed of pyroclastic sediments—breccias and tuffs. Although they are not prominent in the part of the greenstone series exposed along the Eagle River, it seems likely that they constitute at least a fourth and perhaps nearly half of the entire formation in the Keating region.

The coarser breccia members are composed of angular and subrounded fragments of volcanic rock a foot or even more in maximum length, set in a fine-grained chloritic groundmass. In many localities it is difficult to decide whether the somewhat sheared, fragmental-appearing blocks composing a given member of the greenstone series are volcanic bombs and boulders, or originally blocky lava (aa), or whether they are portions of an originally massive flow that have been sheared, rounded in part, and separated by chloritic zones formed during the later deformation of the series. The commonest varieties recognized in such fragmented beds are keratophyres, chiefly non-quartzose, although quartz keratophyre, normal andesite, albite diabase, and locally a few limestone fragments are also represented.

Finer-grained tuffaceous sediments are rather common. Characteristically they are faintly banded rocks whose laminations are emphasized on weathered surfaces. They range in color from gray through buff, light green, dark green, and blue-green to nearly black. Some are dense rocks without megascopically recognizable granular structure or minerals; and others are clearly clastic rocks that contain recognizable feldspar, quartz, and chlorite, or small pellets of volcanic rocks. Many are highly silicified and break with a conchoidal fracture.

In thin section representative specimens of these rocks are seen to be composed chiefly of small angular fragments of rock with separate slivers of individual crystals. Most of the fragments are albitic volcanic rocks, either non-quartzose, with trachytoid or diabasic texture, or quartzose, with rhyolitic texture. Practically all the pyrogenic dark minerals have been altered to epidote-chlorite aggregates, with a little hornblende, although a few crystals of augite remain but slightly altered. Some of the albite is clear and glassy, but much of it contains considerable clinozoisite and epidote and is thus probably an alteration product of an originally more calcic feldspar. This origin is supported by the fact that a few fragments of andesitic rock retain their original andesine. The quartzose keratophyres exhibit marked magmatic corrosion of both quartz and plagioclase phenocrysts.

The crystal slivers common in these rocks plainly can not have been transported any considerable distances. Locally the rocks are cemented with calcite and even contain calcite nodules which are apparently clastic constituents; elsewhere they are silicified.

In addition to the fragmental texture visible both in hand specimens and in thin sections, these rocks have almost all undergone considerable shearing and brecciation at a much later date, so that they contain chlorite seams and are well impregnated with sericite and epidote. Some of these crystal tuffs are so fine grained that they resemble argillites very closely.

The chert and argillite beds are few, thin, and locally restricted; the conglomerate members are apparently discontinuous either by reason of deposition or later deformation and are probably intraformational as they contain, in a chloritic matrix, fairly well-rounded pebbles of volcanic rocks like those with which they are interbedded. Limestone and limestone breccia comprise much less than 1 per cent of the formation; and occur in discrete lenses or pod-shaped masses ranging in size from a few feet to about 2,000 feet long and from a few inches to 400 feet wide. Some of these lenses contain interspersed fragments of volcanic rock, which is probably pyroclastic; but most are rather pure blue-gray limestone that is only locally coarsely recrystallized to marble, although signs of flow are common. The limestones and associated limy pyroclastics carry sparse, poorly preserved fossils.

CHEMICAL COMPOSITION.

Specimens representative of several facies of the greenstone were selected and analyzed chemically, with the results shown in Table 1. For comparison some analyses of other "spilitic" rocks are included.

The similarity of the eastern Oregon rocks to the representative spilitic rocks of Dewey and Flett is obvious. No. 1, of the table page 235, differs in having more potassa than soda but even in this the molecular ratios are 3:2 in favor of soda, while in the others, as in the British spilitic rocks, this ratio is very much higher. In No. 1 there is only enough CaO to satisfy the P_2O_5 present for apatite, so that the feldspar contains no anorthite whatever. Rocks No. 2 and 3 have less than 1 per cent of normative anorthite.

THE "SPILITIC SUITE."

Petrologic attention to the albite-rich lavas was much increased by the appearance, in 1911, of the classic paper by

TABLE 1.

Analyses of rocks from the Permian greenstone of eastern Oregon, and from other "spilitic" associations.

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	72.31	75.04	81.33	66.05	79.64	53.30	59.84	53.15	51.31	51.22	46.01
Al_2O_3	12.76	13.39	9.21	13.29	11.44	15.16	15.71	14.39	12.67	13.66	15.21
Fe_2O_3	1.94	1.61	1.09	3.22	.11	2.54	1.68	1.28	.54	2.84	1.35
FeO	1.26	.37	.74	5.07	.30	8.71	7.03	9.33	7.99	9.20	8.69
MgO	1.32	.18	.40	1.36	.15	4.14	1.37	4.74	2.19	4.55	4.18
CaO	.10	.40	.25	.50	.71	2.97	3.71	7.04	8.17	6.89	8.64
Na_2O	3.69	6.36	3.25	6.67	6.40	5.55	6.52	4.58	5.21	4.93	4.97
K_2O	3.82	.83	1.66	.87	.38	.32	2.76	1.01	.54	.75	.34
H_2O+	1.48	1.07	1.12	1.88	.30	3.14	.31	2.02	2.31	1.88	2.48
H_2O-	.26	.24	.15	.96	.16	.18	.14	.19	.04	...	...
TiO_2	.40	.10	.25	.49	.50	2.41	.64	1.50	1.92	3.32	2.21
P_2O_5	.15	.08	.04	.09	.08	.51	.20	.19	.90	.29	.61
MnO	.08	.05	.05	...	.08	.28	.12	.14	.45	.25	.33
BaO	.09	none	tr?	...	...	none	...	none	nt. fd.	...	...
FeS_2	none	none	none	...	...	.40	[5].10	tr?	.30	...	...
Fe_7S_8	...	...	...	...	...	...	...	...	.17	...	...
CO_2	tr.	.10	.10	...	.02	none	...	.10	6.15	.94	4.98
Sum	99.66	99.82	99.64	100.45	100.27	99.61	100.13	99.66	100.86	100.72	100.00

[5] S, not FeS_2.

1. Quartz keratophyre, west of Balm Creek, in NW. ¼, sec. 29, T. 7 S., R. 43 E., Oregon. J. G. Fairchild, analyst.
2. Quartz keratophyre, SW. ¼, sec. 21, T. 7 S., R. 41 E., Oregon. J. G. Fairchild, analyst.
3. Quartz keratophyre, silicified, SW. ¼, sec. 23, T. 7 S., R. 41 E., Oregon. J. G. Fairchild, analyst.
4. Keratophyre, Trevennen, Cornwall (No. II, p. 209, Dewey and Flett). W. Pollard, analyst.
5. Soda rhyolite, west side of Skomer Island, Wales. (No. III, p. 209, Dewey and Flett.) E. G. Radley, analyst.
6. Albite diabase, No. 2 level, Poorman mine, sec. 32, T. 7 S., R. 43 E., Oregon. J. G. Fairchild, analyst.
7. Albite diabase, Newlyn, Cornwall (No. I, p. 208, Dewey and Flett). W. Pollard, analyst.
8. Spilite, NE. ¼, sec. 35, T. 7 S., R. 42 E., Oregon. J. G. Fairchild, analyst.
9. Spilite, Tayvallich Peninsula, Argyll. (No. I, p. 206, Dewey and Flett.) E. G. Radley, analyst.
10. Average spilite, according to N. Sundius. Geol. Mag. vol. 67, p. 9, 1930.
11. Average spilite, according to A. K. Wells. Geol. Mag. vol. 60, p. 69, 1923.

Dewey and Flett,[6] in which it was pointed out that many of the submarine, usually basic, pillow-lavas are rich in soda and associated with other sodic rocks of a wide range in silica content. The suggestion was made that they are members of a natural family of igneous rocks, the "spilitic" suite, comparable in importance with the "Atlantic" and "Pacific" suites. As defined by them, the "spilitic" suite comprises picrite, albite diabase, minverite (hornblende albite diabase), quartz diabase, spilite, keratophyre, quartz keratophyre, soda-felsite, and albite granite. The essential characteristics of the suite are the abundance of soda feldspar and the common albitization of the rocks, especially of the less siliceous members. This albitization is believed to be a juvenile alteration of the rock masses caused by the same agents that produce the adinoles and cherts commonly associated with them. It is attributed to "pneumatolytic emanations" of uncertain composition but surely rich in water, soda, and silica, and probably in carbon dioxide. Some of the albite, especially of the more siliceous members, they regard as primary. The "spilitic" rocks occur in formations of many ages in the British Isles and elsewhere, and Dewey and Flett believe that they are characteristic of regions of dominant subsidence without important folding. They are the common submarine lavas.

The theory of widespread albitization put forth in the paper of Dewey and Flett was largely based upon, or at least cogently supported by the earlier work of Bailey and Grabham[7] on the alteration of Carboniferous lavas and Permo-Carboniferous intrusions in Scotland. In these rocks albite has replaced the earlier more calcic feldspars on a considerable scale, locally leaving kernels of the original feldspar veined and corroded by albite. The more calcic feldspars seemed especially susceptible to metasomatic albitization, indicating a notable introduction of soda. Though this is true within a given lava, as between distinct flows the more siliceous are the more altered, so that the conclusion was presented that the albitization is due to a kind of autometamorphism (autolysis), the lava "stewing in a concentrated solution of sodium carbonate" of internal derivation. The secondary albite is commonly sericitic or chloritic, but may be water-clear. The intrusive quartz diabase sills carry very numerous albitic segregation veins, testifying to a high concentration of sodic siliceous solutions in these sills late in their consolidation period. The segregation material in the sills was regarded as analogous to the sodic solutions that permeated the lavas.

---

[6] Dewey, H., and Flett, J. S.: Some British pillow-lavas and the rocks associated with them: Geol. Mag., Decade 5, vol. 8, pp. 202-209, 241-248, 1911.

[7] Bailey, E. B., and Grabham, G. W.: Albitization of basic plagioclase feldspars: Geol. Mag., Dec. 5, vol. 6, pp. 250-256, 1909.

Benson[8] studied in great detail the "spilitic" rocks along the serpentine belt of New South Wales where spilites, diabases, keratophyres, quartz dolerites, variolites, and spilitic tuffs are associated with radiolarian chert, jasper, limestone, and shales, and gabbro and serpentine intrusives. Except in the quartz dolerites, which carry andesine, the feldspars are almost all albite or albite-oligoclase. The fresh variolites contain andesine but the altered have albitic feldspars. Some of the rocks carry fresh augite with the sodic feldspar. No adinole occurs at the sill contacts. Many of the rocks, however, show partial or complete albitization of originally more anorthitic feldspar with chloritization of the mafic minerals. The feldspars commonly have inclusions of sericite or paragonite and some are spongy; they are commonly untwinned or poorly twinned.

Despite these features, which suggest a secondary origin of the feldspars, Benson regarded them as primary because of their association in places with fresh augite. In the Tamworth district, however, he believed the keratophyre feldspars secondary, because the phenocrysts consist of albite-calcite masses and octagonal areas of albite appear to represent pseudomorphs of pyroxene. In the associated pyroclastic rocks, too, many albitic feldspars are "obviously" secondary.

The observations of Benson himself,[9] that euhedral fresh augite occurs in vesicles of a Tertiary basalt from the Tamworth district in direct contact with the opal and natrolite filling, demonstrate, however, that augite does not necessarily decompose in contact with hydrothermal solutions and that the association of albite with fresh augite is not decisive of its magmatic origin. This was also the conclusion of Cox,[10] one of the leading British investigators of the "spilitic" rocks.

---

[8] Benson, W. N.: Spilite lavas and radiolarian rocks in New South Wales: Geol. Mag., Decade 5, vol. 10, pp. 17-21, 1913; The geology and petrology of the great serpentine belt of New South Wales: Proc. Linnean Soc. N. S. W., vol. 38, pp. 490-517, 569-596, 662-724, 1913; vol. 40, pp. 121-173, 540-622, 1915.

[9] Benson, W. N.: op. cit., pp. 618-619, 1915.

[10] Cox, A. H.: The geology of the district between Abereiddy and Abercastle, Pembrokeshire: Quart. Jour. Geol. Soc. London, vol. 71, p. 328, 1915.

In the literature pertaining to the "spilitic" rocks a prominent place is taken by the greenstones and keratophyres of the Kiruna district, Sweden. The highly albitic feldspars of the greenstones were at first regarded as original.[11] Upon more exhaustive study, Sundius[12] concluded, because of the regional extent of the albitic rocks, their freedom from contact metamorphic minerals or structures, and the independence of the albitization of any controlling joints, as well as the absence of notable hydration or carbonation (to be expected under the autolysis theory of Dewey and Flett), that the albitization of these rocks is due to regional metasomatism. The cause of the albitization he referred to the instability of the anorthite and the stability of the albite molecules under metamorphic conditions, coupled with the mobility of the potential epidote set free in this process (a sort of regional saussuritization). Over wide areas, this led to practical decalcification of the feldspar but elsewhere caused local concentration of epidote, so that the bulk composition of the formation as a whole may not differ greatly from the original. In parts of the region there are considerable masses of epidote-poor, albitic rocks, which, however, seemed to indicate a large scale expulsion of lime during the metamorphism. Some actual introduction of soda, in solutions derived either from neighboring formations or from other parts of the same formation, was also admitted.[13] The keratophyres associated with the basic greenstones carry flecks of calcic oligoclase (An_{28}) in nearly pure albite crystals. These were interpreted as the residuals left by a slight albitization of these rocks for they contain little epidote but considerable sericite. An emigration of CaO occurred,[14] similar to that in the more basic rocks, but its effect was less striking because of the original composition of the rocks. According to this concept, the so-called keratophyres may be really, in part at least, merely albitized porphyrites. The sericite in the albite can readily be explained by the breaking down of anorthite to zoisite which leaves Al_2O_3 and SiO_2 in excess. If the zoisite emigrates, the excess materials have only to take up alkalies to yield sericite or paragonite.[15] The work of Termier on the rocks of Pelvoux was cited as an example of similar processes.[16] It may be pointed out that the decalcification of the Pelvoux rocks, with concomitant development of residual (though partly recrystallized) albite was thought by Termier to result from the action of percolating meteoric waters; this process could hardly be quantitatively adequate to produce albitization of large rock masses. If the analogy seen by Sundius was merely in the action of moderately heated circulating solutions, it seems that the decomposition of calcic feldspar is explicable, but the large-scale elimination of lime from the formations remains obscure, as does the metasomatic alteration of the plagioclase to albite, while the crystal forms are retained.

---

[11] Lundbohm, H.: (based on observations of Sundius and Zensen) Sketch of the geology of the Kiruna district: Geol. Fören. Förhandl. Bd. 32, p. 757, 1910.

[12] Sundius, N.: Beiträge zur Geologie des südlichen Teils des Kirunagebiets: Vetenskapliga och praktiska Undersötningar i Lappland, pp. 17-76, Uppsala, 1915.

[13] Idem, p. 227.

[14] Op. cit., pp. 233-237.

Sundius' conception of the origin of the Kiruna rocks was criticized by Geijer,[17] who, though accepting the idea that in the Kiruna greenstones the albite replaces an earlier more calcic feldspar, believed that the albite of the associated keratophyres is primary and that the albitization of the less siliceous rocks is a result of Na transfer by hydrothermal solutions derived from the common magmatic source of the two rock groups (autolytic action of Bailey and Grabham).

Sundius' reply to the critique of Geijer was to emphasize again[18] that the alteration of the Kiruna greenstones was more a decalcification of the feldspar than an introduction of Na from an external source. He further criticized the hypothesis of Dewey and Flett on the grounds that the date of albitization is not proved by them to be immediately post-volcanic; that it is unlikely that as much Na can be retained in the hydrothermal solutions as was originally present in the precipitated feldspars; that the absence of albite from the associated cherts, and the absence of relation between albitization and joints are incompatible with the autolysis interpretation. In the Kiruna area the absence of hydrated minerals in the southern part was also regarded as inimical to the hydrothermal theory while explicable on the basis of regional metamorphism at depth too great for their stability. The associated keratophyres were shown to carry relicts of andesine, demonstrating that, contrary to Geijer's theory, the same albitization occurred here as in the more basic rocks. This, according to Sundius, proved that the time of albitization was long after the magmatic period, for the keratophyres are believed to be considerably younger than the greenstones.

---

[15] Op. cit., p. 236; see also Cathrein, Zeitschr. für Krystall., vol. 7, p. 243, cited by Sundius, 1883.

[16] Termier, P.: Sur l'elimination de la chaux par métasomatose dans les roches éruptives basiques de la région du Pelvoux: Bull. Soc. Géol. France, T. 26, pp. 165-192, 1898.

[17] Geijer, P.: Notes on albitization and the magnetite-syenite-porphyries: Geol. Fören. Förhandl. Bd. 38, pp. 243-264, 1916.

[18] Sundius, N.: Zur Frage der Albitisierung im Kirunagebiet: Geol. Fören. Förhandl. Bd. 38, pp. 446-462, 1916.

Wells[19] discussed the spilitic rocks in 1922 and concluded that the independence of the suite as suggested by Dewey and Flett was well established by the absence of association of the spilitic rocks with normal basalts. He even proposed that the name keratophyre be restricted to rocks only of spilitic associations, separating them from bostonites, for example, on this basis.[20] Wells also remarked that the physical conditions of extrusion of the spilites do not alone determine their mineralogic character, as many pillow-lavas have labradorite feldspar and hence the differences between spilites and the normal basalts are original magmatic characters, chiefly higher Na_2O and lower MgO contents. In defense of this thesis he computed an "average spilite" that was quite different from either the "average basalt" or "average nephelite basalt." See Table 1. To explain the common but not invariable albitization of these rocks, he appeals to autolysis, conditioned by the quick chilling during their submarine eruption and formation of an "impervious membrane" imprisoning the residual magmatic liquids.

Eskola,[21] while not accepting the concept of an independent spilitic magma, concluded, from studies of diabasic rocks of Russian Carelia, that the albitization shown by these rocks is due to hydrothermal residual solutions rich in soda and silica, derived from the magma and permeating and replacing the rock body in a late magmatic stage. Naturally such solutions could escape from their source rocks and alter other rock bodies by a sort of contact metamorphism. The ophitic texture shown by several of the rocks he studied, he regarded, from consideration of Bowen's studies of haplobasaltic mixtures, as incompatible with an original feldspar composition so sodic as the existing one and hence as evidence of albitization. Albite and calcite veins, widespread in the region, are regarded as conformable corollaries of this theory. He pointed out, citing observations by several writers, that albitization is not rare in rocks in which pyroxene has been preserved, hence that this association is not evidence of the primary crystallization of albite. The spilitic rocks in his area are associated with normal basaltic rocks of the same geologic age, and regional trends in the distribution of soda can be traced.

---

[19] Wells, A. K.: The nomenclature of the spilitic rocks, Part I, The keratophyric rocks: Geol. Mag., vol. 59, pp. 346-354, 1922; Part II, The problem of the spilites, idem., vol. 60, pp. 62-74, 1923.

[20] The attempt to apply this criterion of "line of descent" in nomenclature would seem questionable, in view of the confusion in parallel cases, such as that of discriminating the essexites from ordinary diabases. Indeed, the keratophyres of Nassau have been attributed to a line of descent distinct from that of the spilites by Brauns (Neues Jahrbuch, Beil. Bd. vol. 27, pp. 320 ff., vol. 28, pp. 411-419, 1909), although in the same paper he was making a plea for the "line of descent" principle in rock nomenclature.

[21] Eskola, Pentti: On the petrology of Eastern Fennoscandia: I, The mineral development of basic rocks in the Karelian formations: Fennia vol. 45, No. 19, 1925.

A comprehensive discussion of the spilite problem, based upon rocks of Swedish Lappland, has been given by Beskow.[22] The association of keratophyres and spilites is recognized here as well as in the Caledonian Mountains of Norway and Great Britain, but both the Lappland rocks are referred by Beskow to a normal basaltic parentage. The spilites are considered to owe their mineralogy to hydrothermal replacements under the influence of heated sea water, the major chemical changes being the leaching out of K, the increase in Na (partly of marine source), and the replacement of part of the SiO_2 by CO_2 in the rocks, while the mineralogic changes include the albitization of the feldspars and the chloritization of the mafic minerals. The work of Beskow shows that most of the British spilites, upon which the concept of a distinct magmatic suite was founded, are, if allowance be made for replacement of SiO_2 by CO_2, of normal basaltic composition. Nevertheless, he agrees that the keratophyres associated with the British rocks, as in the Skomer volcanic series, are, because of their low SiO_2 and high Fe:Mg ratios, probably of alkaline parentage, while insisting that the Lappland keratophyres and quartz keratophyres are the results of a trondhjemitic type of differentiation from a normal basaltic magma. The associated albite granites he regards as products of similar differentiation processes at a later time, since the keratophyres are all preorogenic, the albite granites late-orogenic in age and preceded by less differentiated plutonic rocks. The similarities between the structural and igneous features of Beskow's area and those of eastern Oregon are striking.

---

[22] Beskow, Gunnar: Södra Storfjället im südlichen Lappland: Sver. Geol. Undersökn. Årsbok 21 (1927), Ser. C., No. 350, 1929.

The interesting Kiruna rocks were again discussed by Sundius in 1930.[23] An analysis of a composite sample of an albitic intrusive body in this district has a normative feldspar corresponding to that of a normal diabase or basalt. This confirms, in part, Sundius' earlier conclusion that the epidote has migrated during the metamorphism of the rocks, leading locally to extraordinarily albitic feldspar residua and elsewhere to epidote enrichment, without great changes in bulk composition of the formation as a whole. Nevertheless the variation between the composite and a particular sample were such that he concluded that the mass was originally heterogeneous. His studies of the chemistry of the spilitic rocks led him to the conclusion that they are a distinct magmatic suite, characteristically poor in K_2O and Al_2O_3, high in Na_2O, FeO, and TiO_2 and with a high FeO:MgO ratio. These features inhibit the crystallization of olivine, throw the maximum CaO into the mafic minerals and, by the lowering effect of the high FeO content on the melting point of the pyroxene, displace the equilibrium so that albite crystallizes as a primary mineral contemporaneously with pyroxene. "In this way the textural relations of the rocks are explained without the hypothesis of autometamorphic changes and of an earlier An-rich plagioclase." Sundius makes no effort to reconcile this view with his earlier careful descriptions of relict labradorite in the Kiruna greenstones and andesine in the associated keratophyres.

Backlund has described the Devonian picrites, spilites, quartz keratophyres, and albite diabases of Novaya Zemlya.[24] Of these rocks the albite diabase is most clearly an albitization product, many of his so-called spilites having andesine or even labradorite feldspars. In considering the spilite problem, Backlund concluded that the theory of albitization by the action of marine water finds no support in his area, as none of the rocks is certainly submarine and the intrusive rocks are more albitized than the extrusive. Circulating meteoric solutions, such as were appealed to by Termier at Pelvoux, he excluded because of the intimate association of non-albitic effusives with albitic intrusives. Eskola's theory of autolysis by Na_2SiO_3 solutions he thought incompatible with the relations in Novaya Zemlya, as it leaves unexplained the differences between the effusive and intrusive rocks and the peculiarities of the effusive rocks as such. Sundius' later theory, that the original high FeO:MgO ratio permits retention of the mafics in the magma so that the sodic feldspars can crystallize with them, he believed to be excluded by the absence of albitization in the most vesicular carbonatized and partly epidotized (hence watery), rocks and its presence in the most coarsely crystallized and olivine-bearing varieties. Accordingly he concluded that Dewey and Flett's autolysis theory was best accordant with the facts in his area; and that this autolysis is to be expected in basaltic rocks erupted in dominantly subsiding areas, for these magmas may be expected, in his opinion, to be enriched in volatile constituents, which would lead to a lowering of temperatures of final consolidation and greater crystallization differentiation than those of plateau basalts.

---

[23] Sundius, N.: On the spilitic rocks: Geol. Mag., vol. 67, pp. 1-17, 1930.

[24] Backlund, Helge G.: Die Magmagesteine der Geosynklinale von Nowaja Semlja: Report of the scientific results of the Norwegian expedition to Novaya Zemlya, 1921, especially pp. 23-61, Oslo, 1930.

The spilitic rocks of Dewey and Flett have thus, since 1911, received much attention from European geologists although in America they have been given scant consideration. Daly discussed them briefly[25] and pointed out that inasmuch as it is impossible to distinguish many basalts syngenetic with the typical alkaline rocks of Atlantic suites from basalts of Pacific suites, it is doubly difficult to distinguish spilites, admittedly rocks of basaltic habit, from the basalts of the other suites. Daly further points out the intimate association of the typical German spilites with ordinary basalts and diabases and suggests that their albitization is due to concentration of soda from underlying masses of normal basaltic magma. The especially intense albitization of the submarine spilites is, according to Daly, probably due to the fact that they have been erupted *through* wet sediments of greater or less thickness. Resurgent water from these sediments is supposed to have transferred the soda, and the spilites are regarded by him as pneumatolytic derivatives of normal basaltic magma.

Lewis[26] also regarded the "albitized basic rocks with pillow structure" as "doubtless modified basalts."

[25] Daly, R. A.: Igneous rocks and their origin: New York, pp. 338-340, 1914.

[26] Lewis, J. Volney: Origin of pillow-lavas: Bull. Geol. Soc. Amer., vol. 25, pp. 591-654, 1914.

These divergent interpretations of the spilitic rocks raise, among others, the following questions:

1. Are the spilitic rocks of normal alkali-calcic parentage, as contended by Daly, Sundius (1915), Eskola, and Beskow, or are they derived from an independent magma suite, as thought by Dewey and Flett, Geijer, Wells, Backlund, and Sundius (1930)?

2. Is the soda-rich character determined in the magma, as contended by Dewey and Flett, Daly, Geijer, Wells, Backlund, Sundius (1930), and Eskola, or is it a product of post-magmatic influences as thought by Termier, Sundius (1915), and Beskow?

3. Is their mineral composition (as distinct from their chemical composition) primary throughout as stated by Sundius (1930), and for the more siliceous members by Dewey and Flett, Geijer, Wells, Beskow, and Backlund, or is it largely of metasomatic origin as contended by Termier, Daly, Sundius (1915), Eskola, and for the less siliceous members by all except Sundius (1930)?

In the following section the attempt is made to summarize the information bearing on these questions available in the literature, although it may be well to emphasize in the first place the pertinent remark of Beskow,[27] that since albite and chlorite, the green schist facies of Eskola, are characteristically stable at low temperatures, it should not be surprising that the association may form in more than one way. First it seems desirable to ascertain in how far the associations of the "spilitic" rocks are constant and must be regarded as controlling their genesis.

THE PETROGRAPHIC ASSOCIATIONS OF THE "SPILITIC" ROCKS.

The argument most strongly emphasized by the advocates of a "spilitic suite," distinct from the "alkalic" and the "alkali-calcic" suites, is the supposed constant association of the rocks of the spilitic series and their absence from ordinary alkali-calcic associations.[28] In order to prove the existence of an independent spilitic magma, demonstration of both of these associational generalizations would be required, for there is compelling evidence that both alkalic and subalkalic rocks can be derived from one magma as has been pointed out by several writers, among them Bowen.[29] Hence, if spilitic rocks (granted their primary magmatic origin) occur with normal subalkaline rocks they may well, indeed probably do, have a common parentage. Furthermore, if the minerals of one of the group are demonstrably of metasomatic origin, similar replacements would be expected in the associated rocks so that, to demonstrate magmatic origin, the spilite association should exclude normal alkali-calcic rocks. The associations are accordingly of interest as clues to the question of whether the albitic rocks owe their peculiarities to magmatic differentiation or to subsequent events, and it is a striking and significant fact that there is a very marked association of albitic subsilicic rocks (commonly pillow-lavas and albite-diabases) with keratophyres and quartz keratophyres in many parts of the world.

---

[27] Beskow, G.: op. cit., p. 289.

[28] Dewey, H., and Flett, J. S.: op. cit., p. 209.

Wells, A. K.: The nomenclature of the keratophyres: Geol. Mag., vol. 59, p. 351, 1922; The problem of the spilites: Geol. Mag., vol. 60, pp. 72-74, 1923.

In Europe this association is known from Wales,[30] Devonshire,[31] Scotland,[32] Sweden,[33] Germany,[34] and Greece.[35] In extra-European localities the association is known from New South Wales[36] and many places in the Canadian Shield[37] as well as from eastern Oregon.

---

[29] Bowen, N. L.: The later stages of the evolution of the igneous rocks: Jour. Geol., vol. 23, supplement, pp. 59-60, 1915.

[30] Thomas, H. H.: The Skomer volcanic series, Pembrokeshire: Quart. Jour. Geol. Soc. London, vol. 67, pp. 175-212, 1911.
Cox, A. H.: Note on the igneous rocks of Ordovician age: Rept. Brit. Assoc. Birmingham, pp. 496-498, 1913.
———: The geology of the district between Abereiddy and Abercastle, Pembrokeshire: Quart. Jour. Geol. Soc. London, vol. 71, pp. 273-340, 1915.
———: The geology of the Cader Idris Range, Merioneth: Quart. Jour. Geol. Soc. London, vol. 81, p. 564, 1925.
Greenly, E.: Geology of Anglesey, vol. I: Mem. Geol. Survey Great Britain, pp. 71-76, 1919.
——— and Matley, C. A.: The pre-Cambrian complex and associated rocks of southwestern Lleyn, Carnarvonshire: Quart. Jour. Geol. Soc. London, vol. 84, pp. 454-456, 1928.
Wells, A. K.: The geology of the Rhobell Fawr district, Merioneth: Quart. Jour. Geol. Soc. London, vol. 81, pp. 463-533, 1925.
Stamp, L. D., and Wooldridge, S. W.: The igneous and associated rocks of Llanwrtyd: Quart. Jour. Geol. Soc. London, vol. 79, pp. 18-20, 1923.

[31] Flett, J. S., and Dewey, H.: The geology of Dartmoor: Mem. Geol. Survey Great Britain, p. 19, 1912.
———: The geology of the country around Newton Abbot: Mem. Geol. Survey of Great Britain, pp. 53, 57, 1913.

[32] Flett, J. S.: The geology of Knapdale, Jura and Kintyre: Mem. Geol. Survey of Great Britain, p. 92, 1911.
Balsillie, D.: The Ballantrae igneous complex, S. Ayrshire: Geol. Mag. vol. 69, pp. 107-130, 1932.

[33] Sundius, N.: Zur Frage der Albitisierung im Kirunagebiet: Geol. Fören. Förhandlingar, vol. 38, pp. 446-462, 1916.
Geijer, P.: Pre-Cambrian geology of the iron-bearing region Kiruna-Gällivare-Pajala: Sver. Geol. Undersökn. Årsbok vol. 24, No. 2, ser. C., No. 366, p. 216, 1930.
Beskow, G.: Södra Storfjället im südlichen Lappland: Sver. Geol. Undersökn. Årsbok vol. 21, No. 5, p. 61 ff., 1927 (1929).

Osann[38] considered the quartz keratophyres and keratophyres merely as altered (paleotypal) pantellerites, comendites, and alkaline trachytes, accounting for the usual absence of alkalic mafic minerals by later alteration, an opinion also held by Beskow.[39] Wells,[40] however, has shown that they are chemically and mineralogically distinct, being marked by higher Al_2O_3 and lower Fe_2O_3 and FeO than correspondingly siliceous comendites and alkaline trachytes, thereby accounting for their freedom from alkalic mafics. This corresponds to the commonest usage of the terms and is borne out by the representative analyses given by Rosenbusch.[41]

If the position taken by Wells,[42] in assigning the name keratophyre to albitic effusive and dike rocks only when asso-

---

[34] Pelikan, A.: Die Schalsteine des Fichtelgebirges, aus dem Harz, von Nassau und aus dem Vogesen: Sitzungsber. k. k. Akad. Wiss., Wien, vol. 108, pt. 1, p. 785, 1899.

Brauns, R.: Beiträge zur Kenntnis der chemischen Zusammensetzung der devonischen Eruptivgesteine im Gebiete der Lahn und Dill: Neues Jahrb. für Min., etc., Beil. Bd. 27, p. 320, 1909.

Erdmannsdörfer, O. H.: Ueber die systematische Stellung der harzer Keratophyre: Centr. für Min., pp. 33-41, 1909.

Weber, M.: Ueber Diabase und Keratophyre aus dem Fichtelgebirge: Centralbl. für Min., pp. 37-43, 1910.

Lehmann, E.: Beiträge zur Kenntnis der varistischen Gesteins und Mineralprovinz im Lahn-Dillgebiet: Neues Jahrb. für Min., etc. Beil. Bd. 64 Abt. A., pp. 549-592, 1931.

[35] Ktenas, K. A.: Ueber die eruptiven Bildungen des Parnesgebirges in Attika: Centralbl. für Min., pp. 557-558, 1909.

[36] Benson, W. N.: The geology and petrology of the great serpentine belt of New South Wales: Proc. Linn. Soc. New South Wales, vol. 38, p. 666, 1913, vol. 40, pp. 137, 599, and elsewhere, 1915.

[37] Wilson, M. E.: Kewagama Lake map area, Quebec: Geol. Surv. Canada, Mem. 39, pp. 47-58, 1914.

Cooke, H. C.: Geology of the Matachewan district, northern Ontario: Geol. Surv. Canada, Mem. 115, pp. 11-15, 1919.

Alcock, F. J.: The Reed-Wekusko map area, northern Ontario: Geol. Surv. Canada, Mem. 119, pp. 16-19, 1920.

[38] Rosenbusch, H.: Elemente der Gesteinslehre, 4th edition, by A. Osann, pp. 367-368, 381-382, 1923.

[39] Beskow, G.: op. cit., p. 304.

[40] Wells, A. K.: op. cit., pp. 352-353, 1922.

[41] Rosenbusch, H.: op. cit., p. 366. Rosenbusch states that the absence of alkalic mafic minerals in them and their common association with alkalicalcic rocks suffices to show that some, at least, of the keratophyres and quartz-keratophyres are not derived from alkalic magmas. See Mikroscopische Physiographie der massigen Gesteine, 4th Ed., vol. 2, part 2, pp. 1492-1493, 1908.

[42] Wells, A. K.: op. cit., pp. 350-351, 1922.

ciated with other spilitic rocks is adopted, it is naturally easy to demonstrate the restriction of keratophyres to the spilitic association. Similarly, by selecting analyses for the purpose of illustrating the independence of a rock type, as has been done by Sundius[43] in his compilation of spilitic rocks, it is possible to establish a large hiatus between the spilites and more normal basalts. This seems to the writer a matter of definition, not the recognition of natural relationships, and a study of analyses of submarine and related rocks appears to show complete gradation from perfectly normal basalts to highly albitic spilites, with no real gaps between them. That the distinction of the spilites and albite diabases from normal basaltic rocks is not objectively established seems clear from inspection of the pronounced differences between the average spilite as computed by Wells and that by Sundius, both based on analyses chosen to exclude transition rocks. See Table 1, page 235.

Accordingly, it appears justifiable to include with the rocks of the above mentioned localities, such as have highly albitic feldspars, low K_2O and no notably sodic pyriboles, and to ascertain in how far their associations are exclusive of normal basalts and diabases with labradorite or andesine feldspars.

As has been emphasized by Daly[44] for the German spilites, and shown by the work of many other petrologists cited below, normal basalt and diabase occur with keratophyres or spilites or both in Wales,[45] Derbyshire,[46] Scotland,[47] Norway,[48] Sweden,[49] Finland,[50] Germany,[51] Czechoslovakia,[52] Switzerland,[53] as well as in New South Wales[54] and Canada.[55] In the western United States the keratophyres are by no means restricted to associations containing other albitic rocks. The Triassic keratophyres of Nevada[56] are intimately associated with normal andesites and potash-rich trachytes, those of the Mother Lode (Jurassic) with apparently normal basalts,[57] and the Tertiary keratophyres of Nevada with andesites[58] or basalts.[59] The eastern Oregon keratophyres and spilites are associated with a few normal andesites and basalts.

---

[43] Sundius, N.: On the spilitic rocks: Geol. Mag., vol. 67, pp. 7-11, 1930.

[44] Daly, R. A.: op. cit., pp. 338-339.

[45] Thomas, H. H.: The Skomer volcanic series, Pembrokeshire: Geol. Soc. London, Quart. Jour., vol. 67, pp. 201-204, 1911.

Wells, A. K.: The geology of the Rhobell Fawr district, Merioneth: Geol. Soc. London, Quart. Jour., vol. 81, pp. 511, 513, 523, and elsewhere, 1925.

Williams, D.: Geology of the country between Nant Peris and Nant Ffrancon: Geol. Soc. London, Quart. Jour., vol. 86, pp. 208, 223, 1930.

[46] Sargent, H. C.: On a spilitic facies of Lower Carboniferous lava-flows in Derbyshire: Geol. Soc. London, Quart. Jour., vol. 73, pp. 17-23, 1917.

[47] Balsillie, D.: The Ballantrae igneous complex, S. Ayrshire: Geol. Mag., vol. 69, p. 110, 1932.

[48] Goldschmidt, V. M.: Geologische-petrographische Studien im Hochgebirge des südlichen Norwegens, IV., Uebersicht der Eruptivgesteine im kaledonischen Gebirge zwischen Stavanger und Trondhjem: Vidensk. Skrifter, 1, analyses on p. 15, 1916.

Carstens, C. W.: Der unterordovicische Vulkanhorizont in dem Trondhjemgebiet, Norsk Geol. Tidsk., vol. 7, pp. 207-208, 1924.

[49] Sundius, N.: Geologie des Kirunagebiets: Vetenskapliga praktiska Undersökninger i Lappland anordnede av Luossavaara-Kirunavaara Aktiebolog. vol. 4, p. 62, Uppsala, 1915.

Beskow, G.: op. cit., p. 291.

It is true that several of these albite-rich rocks would not fall within the rigorous limits permitted to spilites by either Wells or Sundius, though many do, and have been cited as "typical," but in view of the divergences noted above between the "average spilites" of these two writers, the list indicates the absence of antipathy between a "spilitic" association and "normal" basalts.

The question of chemical distinction between spilites and other rocks has been approached by Hackman,[60] who plotted many analyses on Hommel's projection. He found that the British and Australian spilites appear intermediate between gabbro and essexite, the Aunus (Carelia) rocks chiefly in the monzonite field, the Kiruna rocks are widespread in all fields.

[50] Hackman, V.: Studien über den Gesteinsaufbau der Kittilä-Lappmark: Bull. Comm. Géol. de Finland, No. 79, p. 17, 1927.
Eskola, P.: op. cit., pp. 17, 78-79.

[51] Erdmannsdörfer, O. H.: op. cit., pp. 33-41, 1909.
Lehmann, E.: Beiträge zur Kenntnis der varistischen Gesteins- und Mineralprovinz im Lahn-Dillgebiet: Neues Jahrb. für Min. Geol. und Paläontologie, Beil. Bd. 64, Abt. A., pp. 549-592, 1931.
Pelikan, A.: op. cit., pp. 749-754, 763-765.
Brauns, R.: op. cit., pp. 411-420.
Weber, M.: op. cit., p. 43.

[52] Kettner, R.: Versuch einer stratigraphischen Einteilung des böhmischen Algonkiums: Geol. Rundschau, vol. 8, p. 173, 1917.

[53] Grubenmann, U.: Beiträge zur Geologie des Unterengadins: Beitr. zur geol. Karte der Schweiz. No. 23, pp. 232-244, 1909.

[54] Benson, W. N.: op. cit. Proc. Linn. Soc. N. S. W., vol. 38, pp. 509-510, 667, and elsewhere, 1913.

[55] Alcock, F. J.: op. cit., pp. 16-17.

[56] Knopf, Adolph: Geology and ore deposits of the Yerington district, Nevada: U. S. Geol. Surv. Prof. Paper 114, pp. 13-16, 1918; Geology and ore deposits of the Rochester district, Nevada: U. S. Geol. Surv. Bull. 762, pp. 20, 22, 1924.

[57] Knopf, Adolph: The Mother Lode system of California: U. S. Geol. Surv. Prof. Paper 157, pp. 14-18, 1929.

[58] Knopf, Adolph: Ore deposits of Cedar Mountain, Mineral County, Nev.: U. S. Geol. Survey Bull. 725, p. 368, 1921.

[59] Nolan, T. B.: Underground geology of the western part of the Tonopah Mining district, Nevada: Univ. of Nevada Bull., vol. 24, No. 4, p. 15, 1930.

[60] Hackman, V.: Studien über den Gesteinsaufbau der Kittilä-Lappmark: Bull. Comm. Géol. de Finlande, No. 79, pp. 35-36, 1927.

Inasmuch as the projections prove the spilites to have a considerable range, including rocks of the gabbro, anorthosite, essexite, and monzonite fields, he concluded that in the sense that gabbro is an independent magma type the spilites are not, but that they may reasonably be regarded as a geologic group because they are all more or less related basic eruptives, chiefly effusive, which have all undergone similar metamorphism, either autolytic or regional metasomatic.

Beskow[61] also made a thorough study of the analyses of spilites. He reached the conclusions that Hackman's projection method (in which the CO_2 was rejected but no correction to the lime made) was in conformity with Wells' assumption that the present mineral composition of the spilites is entirely autogenous and that, on this assumption, Hackman's conclusion that the spilites are not a unified rock group distinct from others was sound. Beskow's own computations, however, were made on the contrasted assumption that the CO_2 present in the rocks has replaced SiO_2 which has migrated from them. On this assumption he found a remarkable agreement among the spilites themselves and between them and quite normal basalts when all were plotted in the triangle involving the Niggli ratios for Femca Alk-SiO_2. His conclusion was that they constitute merely a peculiarly altered group of normal basalts in which the alteration was exogenous.

The available analyses representing spilitic associations, compiled by the writer, are plotted in the normative feldspar triangle of Fig. 2. The analyses have been computed without regard to CO_2 which of course assumes the CaO to have been originally present in anorthite. From the plotted feldspar compositions there seems to be a complete gradation from the spilitic to the normal subalkaline rocks. The only persistent feature shown by these analyses is poverty in K_2O. This is discussed in Part II.

The associational and analytical data thus seem to render untenable the hypothesis of an independent magma type as the source of all spilitic rocks. They do not, however, exclude a magmatic origin for the peculiarities of the rocks, since magmatic differentiation may have produced offshoots, abnormal in greater or less degree, from a normal series,—thus accounting for the striking, though clearly not exclusive, association of keratophyres and spilites.

---

[61] Beskow, G.: op. cit., pp. 279-311, criticism of Hackman in footnote, p. 292.

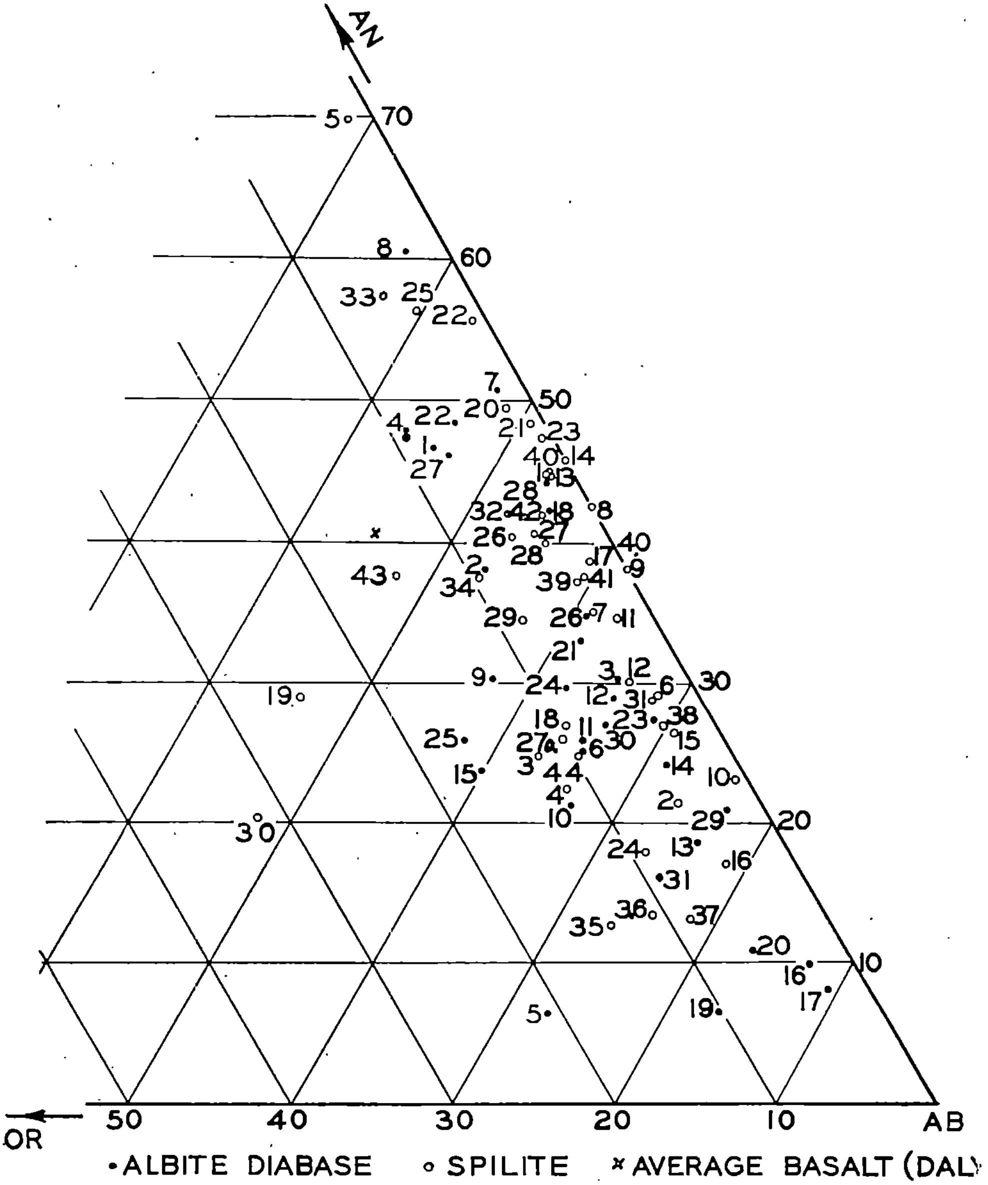


Fig. 2. Molecular percentages of normative feldspars of spilites and albite diabases with the average basalt of Daly. For rock analyses used in this figure see table on page 235.

If this conclusion is sound, that the parent magma of the keratophyres and spilites is not notably abnormal, it becomes of interest to investigate the geologic environment of the rocks to ascertain, if possible, what factors determine their peculiar mineralogy. Prominent among the environmental features which have been regarded as of genetic significance in the "spilite problem," is the common association with marine sediments in a manner suggesting eruption of the rocks under submarine conditions. The influence of the marine environment, if it is general with these rocks, may be thought of as direct: due to circulating sea water (Beskow), to quick chilling and consequent retention of volatiles (Wells); or as indirect: passage of the eruptive through watery sediments (Daly), absorption of wet sediments (Daly, Goldschmidt?) or to an obscure control of magmatic evolution under the tectonic condition of the continuous sinking of the sea floor (Dewey and Flett).

GEOLOGIC ENVIRONMENT OF THE ALBITIC VOLCANIC ROCKS.

Spilites or keratophyres are associated with marine sediments in such manner as to suggest their submarine eruption in Australia,[62] East Indies,[63] Germany,[64] Czechoslovakia,[65] Norway,[66] Sweden,[67] Wales,[68] Cornwall,[69] and Devon.[70] In

---

[62] Benson, W. N.: Spilite lavas and radiolarian rocks in New South Wales: Geol. Mag., pp. 17-21, 1913; The geology and petrology of the great serpentine belt of New South Wales: Proc. Linnean Soc. N. S. W., vol. 38, pp. 574-575, vol. 40, pp. 123, 130, 1915.

[63] Verbeek, R. D. M.: Description géologique de l'île d'Ambon; Jaarb. van het Mijnwezen in Nederl. Oost Ind. Batavia, vol. 34, p. 126, 1905.

[64] Brauns, R.: Beiträge zur Kenntnis der chemischen Zusammensetzung der devonischen Eruptivgesteine im Gebiete der Lahn und Dill: Neues Jahrb. Beil. Bd. 28, pp. 391-393, 1909.

Pelikan, A.: Die Schalsteine des Fichtelgebirges, aus dem Harz, von Nassau und aus dem Vogesen: Sitzungsber. k. k. Akad. Wiss., Wien, Bd. 108, H. 1, p. 789, 1899.

[65] Kettner, R.: Versuch einer stratigraphischen Einteilung des böhmischen Algonkiums: Geol. Rundschau, Bd. 8, p. 174, 1917.

[66] Carstens, C. W.: Der unterordovicische Vulkanhorizont in dem Trondhjemgebiet, Norsk Geol. Tidsk. vol. 7, pp. 192-193, 1924.

Goldschmidt, V. M.: Geologische-petrographische Studien im Hochgebirge des südlichen Norwegens, IV., Uebersicht der Eruptivgesteine im kaledonischen Gebirge zwischen Stavanger und Trondhjem; Vidensk. Skr. 1, p. 10, 1916.

[67] Beskow, G.: op. cit., pp. 39-127.

[68] Cox, A. H., and Jones, O. T.: On various occurrences of pillow-lavas in North and South Wales: Geol. Mag. Decade V, vol. 10, pp. 516-517, 1913.

———: op. cit. supra. 1915, pp. 307-310, 1913, pp. 496-498.

Thomas, H. H.: op. cit., pp. 209-210, 1911.

Greenly, E.: op. cit., pp. 71-76, 1919.

Matley, C. A.: op. cit., pp. 464-466.

America, the Triassic keratophyres of Nevada[71] are interbedded with marine sediments as are the Jurassic keratophyres of the Mother Lode country[72] of California and the Permian rocks of eastern Oregon. Several occurrences of basaltic rocks of probable submarine origin whose analyses suggest that they are albitic, although conclusive microscopic evidence has not been presented respecting them, are found in America. These include the ellipsoidal greenstones from the Crystal Falls district, Michigan,[73] and the ellipsoidal basalts of Point Bonita, California.[74]

Although it is seen that many of these spilites and keratophyres are of submarine origin, the Tertiary keratophyres of Nevada[75] are definitely sub-aerial and so are the Ordovician Skomer rocks,[76] of Wales, at least some of the ultra-sodic hälleflintas of Sweden,[77] and possibly the spilites of Novaya Zemlya,[78] although Backlund's conclusion as to their environment does not appear to rest on compelling evidence. The conclusion seems permissible that although the "spilitic" rocks are chiefly products of submarine eruption this locus is not essential for their development—nor conversely, do all submarine volcanics fall into this group.

---

[69] Flett, J. S., and Hill, J. B.: Geology of the Lizard and Meneage: Mem. Geol. Survey Great Britain, p. 177, 1912.

[70] ——— and Dewey, H.: The geology of Dartmoor: Mem. Geol. Surv. Great Britain, p. 19, 1912.

[71] Knopf, A.: Geology and ore deposits of the Yerington district, Nevada: U. S. Geol. Surv. Prof. Paper 114, pp. 13-16, 1918.

[72] Knopf, A.: The Mother Lode system of California: U. S. Geol. Survey Prof. Paper 157, pp. 14-18, 1929.

[73] Clements, J. M.: The Crystal Falls iron-bearing district of Michigan: U. S. Geol. Survey Mon. 36, p. 106, 1899. As has been pointed out by Sundius, the extinction angles given by Clements (17°-18°) as characterizing the "labradorite" are compatible with the feldspar being albite, as is suggested by the rock analysis.

[74] Ransome, F. L.: The eruptive rocks of Point Bonita: Univ. of California Dept. of Geology Bull., vol. 1, pp. 77-114, 1893.

[75] Knopf, A.: Ore deposits of Cedar Mountain, Mineral Co., Nevada: U. S. Geol. Survey Bull. 725, p. 368, 1921.

Nolan, T. B.: Underground geology of the western part of the Tonopah mining district, Nevada: Univ. of Nevada Bull., vol. 24, No. 4, p. 15, 1930.

[76] Thomas, H. H.: op. cit., p. 175.

[77] Sundius, Nils: Grythyttefältets geologi: Sver. Geol. Undersökn. Ser. C, No. 312, p. 340, 1922.

[78] Backlund, A. G.: op. cit., pp. 37-40.

GEOLOGICAL SURVEY,
WASHINGTON, D. C.

(Continued in next issue.)

THE PERIOD OF RADIUM.

ELLEN GLEDITSCH AND ERNST FÖYN.

Some time ago we published the results of a new determination of the period of radium. The experiment was done on a sample of broeggerite from Karlshus, Norway, and the result, $4{,}10 \,.\, 10^{-4}$ agreed very well with the result, $4{,}11 \,.\, 10^{-4}$ obtained earlier by one of us.[1]

We had at this time also made determinations of the constant, using another Norwegian uraninite, cleveite. Like broeggerite, cleveite is found in pegmatite dikes, which cut massifs of granite. These belong to the pre-Cambrian period, and the ages of the two minerals, as determined from radioactive data, are 900 and 1000 million years.[2] Broeggerite is undoubtedly very fresh and unaltered, cleveite perhaps not quite as good. The black lumps and crystals of which the mineral consists show streaks of yellow uranium products, and analyses prove that the ratio UO_2/UO_3 is considerably less than in broeggerite. X-ray crystallographic examination also indicates a slight alteration.[3]

We have put together in Table I analyses of the cleveites examined and of the broeggerite used in the earlier experiment.

TABLE 1.

	Cleveite from Austagder (No. 10)	Cleveite from Austagder (No. 116)	Broeggerite from Karlshus Raade (No. 39)
UO_3	44,80	46,12	24,30
UO_2	33,57	32,63	52,67
ThO_2	0,91	2,58	7,85
PbO	11,40	12,05	9,63
Rare earth oxides	1,00	2,75	1,16
SiO_2	0,34	0,32	0,20
Fe_2O_3	0,52	2,98	0,36
Al_2O_3	0,09	....	0,05
CaO	0,56	....	0,45
UO_2/UO_3	0,75	0,71	2,3
Ra	$2{,}27 . 10^{-5}$	$2{,}28 . 10^{-5}$	$2{,}20 . 10^{-3}$
Ra/U	$3{,}38 . 10^{-7}$	$3{,}38 . 10^{-7}$	$3{,}38 . 10^{-7}$
Pb/U + 0,36.Th	0,156	0,164	0,133

---

[1] Gleditsch and Föyn: this Journal, XXIV, p. 387, 1932.
E. Gleditsch: Archiv for Math. og Naturvidenskap B. 36, No. 1, 1919.

[2] E. Gleditsch: Det Norske Videnskapsakademi i Oslo I, No. 3, 1925.

[3] Goldschmidt and Thomassen: Videnskapsakademiets skrifter Oslo. I, No. 2, 1923.

In Table 2, 3 and 4 follow the measurements of the growth of radon in the ionium solutions prepared from the three mineral samples. As for the method, we refer to Boltwood's work on this question and to our earlier papers.[4, 1]

TABLE 2.

Cleveite from Austagder (No. 10).

100 g. of mineral, containing $2,27.10^{-5}$ g. radium, was dissolved and the ionium solution and the test solution prepared in the usual way. The test solution showed no increase of radium.

Growth of radium in the ionium solution.

Test No.	Time from start in days	Radon found in curies	Growth of radium per day
1	48,5	$1,06.10^{-9}$	
2	97,6	$2,33.10^{-9}$	$0,02585.10^{-9}$
3	131,5	$3,23.10^{-9}$	$0,02614.10^{-9}$
4	161,5	$3,97.10^{-9}$	$0,02561.10^{-9}$

The amount of radium in the solution at the start was too small to be determined.

The average amount of radium produced was $0,02587.10^{-9}$ g. per day or $9,44.10^{-9}$ g. per year.

$$\lambda_{Ra} = \frac{9,44.10^{-9}}{2,27.10^{-5}} = 4,16.10^{-4}$$

$$T_{Ra} = \underline{\underline{1666 \text{ years.}}}$$

TABLE 3.

Cleveite from Austagder (No. 116).

40 g. of mineral, containing $0,912.10^{-5}$ g. radium, was dissolved and the ionium solution and the test solution prepared in the usual way. The test solution showed no increase of radium.

Growth of radium in the ionium solution.

Test No.	Time from start in days	Radon found in curies	Growth of radium per day
1	1,8	$1,30.10^{-9}$	
2	79	$5,00.10^{-9}$	
3	680	$11,43.10^{-9}$	$0,0102.10^{-9}$
4	704	$12,11.10^{-9}$	$0,0106.10^{-9}$

The amount of radium in the solution at the start was $4,6.10^{-9}$.

---

[4] Boltwood: this Journal, 25, 493, 1908.

The average amount of radium produced was $0{,}0104.10^{-9}$ g. per day or $3{,}796.10^{-9}$ g. per year.

$$\lambda_{Ra} = \frac{3{,}796.10^{-9}}{0{,}912.10^{-5}} = 4{,}16.10^{-4}$$

$$T_{Ra} = \underline{\underline{1666 \text{ years.}}}$$

TABLE 4.

Broeggerite from Karlshus, Raade (No. 39).

93,4 g. of mineral, containing $2{,}05.10^{-5}$ g. of radium, was dissolved, and the ionium solution and the test solution prepared. The test solution showed no increase in radium.

Growth of radium in the ionium solution.

Test No.	Time from start in days	Radon found in curies	Growth of radium per day
1	3,5	$0{,}174.10^{-9}$	
2	35,56	$1{,}030.10^{-9}$	$0{,}0229.10^{-9}$
3	108,5	$2{,}715.10^{-9}$	$0{,}0231.10^{-9}$
4	147,5	$3{,}630.10^{-9}$	$0{,}0233.10^{-9}$
5	333	$7{,}778.10^{-9}$	$0{,}0230.10^{-9}$

The amount of radium in the solution at the start was $0{,}33.10^{-9}$ g.

The average amount of radium produced was $0{,}0231.10^{-9}$ g. per day or $8{,}422.10^{-9}$ g. per year.

$$\lambda_{Ra} = \frac{8{,}422.10^{-9}}{2{,}05.10^{-5}} = 4{,}10.10^{-4}$$

$$T_{Ra} = \underline{\underline{1691 \text{ years.}}}$$

It will be noticed that the periods found for the cleveites agree closely, but that they differ a little from the value found for the broeggerite, both the last one and the earlier. The difference is small enough to be considered as an inevitable experimental error. However, earlier experiments on the two minerals made us reluctant to believe this. We rather felt that it might be due to a slight alteration in the cleveite. This is indicated also by the low value for the ratio UO_2/UO_3; on the other hand the alteration must be very slight as the ratio Ra/U is the normal one.

In any case we felt that we should like to confirm the results from the broeggerite on a mineral that was equally good and unaltered, but differed in age and origin.

This was made possible for us by the help of Professor A. Knopf at Yale and Dr. W. F. Foshag at the Smithsonian Institution, Washington, who provided us with a specimen of uraninite from Spruce Pine, North Carolina. This uraninite is considered unaltered and it is at the same time considerably more recent than broeggerite, about 250 million years old. We are glad to express here our gratitude for this valuable help.

We started one experiment on this material and simultaneously one on a sample of broeggerite, the same that had served for the earlier experiment. We decided this time to use less material, 25 to 40 g., hoping thereby to be able to conduct the chemical operations in a very careful and exact way.

The details of the chemical treatment have been described earlier.[1] The small amounts of mineral made it necessary to leave the ionium solutions in which the radon was to be determined, for longer periods. The procedure followed in measuring the growing quantities of radon and the way of calculating the growth has been described in earlier papers.[1, 4] The only change introduced has been the following: instead of making at a given time from the start only one measurement, we made two or three measurements, following each other at an interval of a few days, and used the average value, applying a correction for the later measurements where the equilibrium value had not been reached.[1]

Uraninite

from Deer Park Mine, Spruce Pine, N. C. (No. 119).

The mineral was pulverised, a small sample kept for analyses, and the rest, 23.49 g., was used for the experiment. We made no full analysis of the mineral, owing to the small amount available, and determined only the radioactive data necessary, but we reproduce in Table 5 two analyses of uraninites from Flat Rock mine, Spruce Pine, in North Carolina, due to Hillebrand.[5]

---

[5] Bull. U. S. Geol. Survey No. 77, p. 43, 1891.

TABLE 5.

UO_3	50,83	44,11
UO_2	39,31	46,56
ThO_2	2,78	3,04
Rare earth oxides	0,90	
PbO	4,20	4,53
FeO	tr.	tr.
CaO	0,85	0,23
MgO Alk.	0,30	0,25
H_2O	1,21	undet.
SiO_2	0,08	0,13
Insol.	0,10	0,06

23,49 g. of mineral, containing $0,5544.10^{-5}$ g. radium, was dissolved, and the ionium solution and the test solution prepared in the usual way. We replaced, however, the solution of rare earths, that had been added in previous experiments in order to ensure the precipitation of the ionium, by a solution of pure lanthanum nitrate. This was done because we expected to use the ionium solution later for some experiments on actinium. In preparing the main solution 0.7200 g. La $(NO_3)_3$ was added, and in the test solution 0.6180 g. The test solution showed no increase in radium.

Growth of radium in the ionium solution.

Test No.	Time from start in days	Radon found in curies	Growth of radium per day
1	3,26	$0,522.10^{-9}$	
2	175	$2,204.10^{-9}$	$0,00633.10^{-9}$
3	522	$4,358.10^{-9}$	$0,00624.10^{-9}$
4	566	$4,640.10^{-9}$	$0,00626.10^{-9}$

The amount of radium in the solution at the start was $1,11.10^{-9}$ g.

The average amount of radium produced was $0,00628.10^{-9}$ g. per day or $2.293.10^{-9}$ g. per year.

$$\lambda_{Ra} = \frac{2,293\ .10^{-9}}{0,5544.10^{-5}} = 4,13.10^{-4}$$

$$T_{Ra} = \underline{\underline{1678 \text{ years.}}}$$

Broeggerite

from Karlshus, Raade, Norway (No. 39).

The mineral was described in an earlier paper[1] and the analysis is given in Table 1.

40 g. of mineral containing $0,88.10^{-5}$ g. radium, was dissolved and the ionium solution and the test solution prepared in the usual way. The test solution showed no increase in radium.

Growth of radium in the ionium solution.

Test No.	Time from start in days	Radon found in curies	Growth of radium per day
1	2,8	$0,103.10^{-9}$	
2	125	$1,513.10^{-9}$	$0,0103\ .10^{-9}$
3	723	$7,395.10^{-9}$	$0,00985.10^{-9}$
4	727	$7,396.10^{-9}$	$0,00985.10^{-9}$

The radium present in the solution at the start was $0,27.10^{-9}$ g.

The average amount of radium produced was $0,00999.10^{-9}$ g. per day or $3,645.10^{-9}$ g. per year.

$$\lambda_{Ra} = \frac{3,645.10^{-9}}{0,88\ .10^{-5}} = 4,12.10^{-4}$$

$$T_{Ra} = \underline{\underline{1682 \text{ years.}}}$$

The results found in the different experiments have been put together in Table 6.

TABLE 6.

Mineral:	λ_{Ra}	Period—T_{Ra}
1. Broeggerite	$4,11.10^{-4}$	1686
2. Broeggerite (39)	$4,10.10^{-4}$	1691
3. Broeggerite (39)	$4,12.10^{-4}$	1682
4. Uraninite (119)	$4,13.10^{-4}$	1678
5. Cleveite (10)	$4,16.10^{-4}$	1666
6. Cleveite (116)	$4,16.10^{-4}$	1666

The values of the radioactive constant of radium, found in the experiments on uraninite, North Carolina, and broeggerite, Norway, agree closely. They also agree with values found in earlier experiments on broeggerite. We have no doubt, therefore, that the mean value of these four determinations

$$\lambda_{Ra} = 4,11 \times 10^{-4} \frac{1}{\text{year}}$$

is the correct one. It is also in perfect accordance with the value deduced by Kovarik and Adams,[6] from the experiments on the number of α-particles from uranium.

The difference between this value and the one found in experiments on two different samples of cleveite (from the same locality, however), is slight, but seems to us to be definite. We are inclined to believe that this is due to a slight alteration in the cleveites. This view is corroborated by the X-ray examination of broeggerite and cleveite,[4] and by the fact that the ratio UO_2/UO_3 is small in cleveite compared with the ratio in certain other uraninites. The alteration in the crystal lattice will increase the possibilities for leaching, and a slight leaching that had affected especially the radium in the mineral, would account for the higher value of the constant.

---

[6] Kovarik and Adams: Phys. Rev. II 40. 7-18, 1932.

That the leaching is very slight is proved by the small difference between the transformation constant of radium found in cleveite and in the other uraninites, and also by the analyses, which, for these two cleveites, give the normal value for the ratio radium/uranium. That an eventual leaching would preferably attack the radium and not the ionium in the mineral, is in accordance with results obtained earlier on uranothorites.[7]

CONCLUSIONS.

The constant of radium has been determined through experiments on two unaltered minerals, uraninite from Spruce Pine, North Carolina, and broeggerite from Karlshus, Raade, Norway. The method is the one first used by Boltwood and later by us. A few changes have been introduced in order to increase the exactness and eliminate possible errors. The results

$$\lambda_{Ra} = 4{,}12.10^{-4}\frac{1}{\text{year}} \text{ and } 4{,}13.10^{-4}\frac{1}{\text{year}}$$

agree with earlier results from other samples of broeggerite, viz.:

$$\lambda_{Ra} = 4{,}10.10^{-4}\frac{1}{\text{year}} \text{ and } \lambda_{Ra} = 4{,}11.10^{-4}\frac{1}{\text{year}}.$$

The mean value of these determinations give

$$\lambda_{Ra} = 4{,}11.10^{-4}\frac{1}{\text{year}},$$

corresponding to a period of 1686 years.

---

[7] Gleditsch and Qviller: Phil. Mag. 7, vol. XIV, p. 233, 1932.

UNIVERSITY OF OSLO,
NORWAY.

A STUDY OF THE SYSTEM LIME-POTASH-ALUMINA.*

L. T. BROWNMILLER.

INTRODUCTION.

In non-metallic mineral chemistry, lime, silica and alumina occupy predominant rôles in consequence to their wide distribution and their extensive utilization in industry. Hence it was logical that the earlier thermal studies for determining the relations of the oxides to one another should be focused on the ternary system CaO-SiO_2-Al_2O_3. The classical work of Rankin and Wright (1) has developed the thermal characteristics and phase relations of that system.

In itself, that work is inadequate for the final solution of the problems encountered in the silicate and allied industries. The influence of other oxides which are usually associated with the lime, alumina and silicate minerals must be determined. But as a consequence of the complications attending a study of the systems of more than three components, the final relations of the oxides to each other are most conveniently determined by an investigation of a series of ternary systems.

An extensive study of oxide systems, especially those involving silica, has been undertaken at the Geophysical Laboratory in Washington (2). Numerous other investigations of ternary oxide systems have been completed. The system CaO-Fe_2O_3-SiO_2 was studied by Hansen and Bogue (3). Al_2O_3 and Fe_2O_3 have been studied together and in combination with CaO (4) and with MgO (5) by Hansen, Brownmiller and Bogue. A ternary system of more complex components, the system $5CaO.3Al_2O_3$-$2CaO.SiO_2$-CaO was solved by Hansen (6). The system CaO-Na_2O-Al_2O_3 was investigated by Brownmiller and Bogue (7).

The studies reported in this paper have extended the series to include the compound K_2O in combination with CaO and Al_2O_3. The portion of this system chosen for the most detailed investigation is that which is of immediate industrial importance,—namely that portion limited to the smaller percentages of potash.

The results of the studies are significant wherever potash is utilized in the presence of CaO and Al_2O_3 at high temperatures, particularly in the cement and ceramic industries.

---

* Publication approved by the Director of the National Bureau of Standards, U. S. Department of Commerce, Paper No. 30 of the Portland Cement Association Fellowship at the Bureau of Standards.

EXPERIMENTAL METHOD.

The method of establishing the equilibrium conditions in the ternary system consisted in the preparation of specific compositions over the portion of system to be studied. The heat-treated samples were subsequently examined microscopically and by means of X-rays. The temperature at which the last crystals disappeared on heating, or at which the first crystals were observed on cooling, was taken as the melting temperature of the sample. The general procedure for establishing equilibrium was similar to that used in the study of the system $CaO-Na_2O-Al_2O_3$.

In this work, however, special attention had to be paid to the volatility of the potash. In order to insure the accuracy of the final compositions upon which temperature measurements were made, the relative proportions of the oxides were controlled by weight. The effect of the volatility of the potash was checked by analysis. And the consistency with which the melting temperatures and the phase relations of a single composition could be rechecked, gave evidence that the amount lost by volatilization was small. These matters are presented in some detail, especially where new problems over those of the soda system were encountered.

The raw materials for the studies were obtained from the Portland Cement Association Fellowship at the Bureau of Standards in Washington. The analyses of these materials are indicated in Table I.

TABLE I.

Partial Analyses of Raw Materials.

Calcium Carbonate* Per cent		Alumina* Per cent		Potassium Oxalate** Per cent	
CaO	56.04	Al_2O_3	98.48	Cl	0.005
MgO	.07	SiO_2	.01	Fe	0.001
R_2O	.06	Fe_2O_3	.002	Other heavy metals	None
R_2O_3	.05	CaO	Nil		
SiO_2	.01	Cl	Trace	SO_3	0.02
Ignition Loss	43.71	SO_3	Trace		
		Ignition Loss	1.42		

* Analysis by Carlson, Bureau of Standards.
** Analysis by manufacturer.

In the preparation of the samples base compositions of CaO and Al_2O_3 were weighed in various proportions and thoroughly mixed in a small amount of water. These mixtures were then heated at about 1350° C. in a platinum resistance furnace. A portion of this base composition was accurately weighed and to it the third component, K_2O, was added in the form of potassium oxalate. This compound of potassium was used because it is only slightly deliquescent and, therefore, presented no great difficulties in weighing.

The ternary composition was dry mixed and heated at a temperature of about 1200° C. A relatively low temperature was used for the first heating because by this procedure less K_2O was lost by volatilization than obtained with higher initial heating temperatures. The samples were then reheated at 1500° C. All preliminary heating was done in open platinum vessels in the platinum resistance furnace referred to previously. After cooling in a desiccator, the samples were reweighed and from the increase in weight the amount of K_2O in the mixture was calculated.

Some data on the volatility of K_2O from samples during the heating at 1500° C. in open platinum vessels are given in Table II. The samples were in the hot zone of the furnace for about thirty minutes. The amount of K_2O lost on the second heating at 1500° C., that is after combination had been effected, was found to be less than 10% of the total K_2O present. Since most of the compositions studied contained less than 10% K_2O, the actual amount lost would be less than 1% K_2O. Furthermore, the samples used for the temperature determinations were always tightly enclosed in platinum foil, and the amount of K_2O lost would be considerably less than the amount lost on heating in the open platinum crucibles. Morgan (8) performed somewhat analogous experiments which revealed losses of K_2O comparable to those reported here from open platinum crucibles.

TABLE II.

Heat Treatment		Sample A	Sample B	Sample C
First heating (1200° C)	CaO—	46.9%	49.4%	39.8%
	K_2O—	9.0%	4.9%	11.2%
	Al_2O_3—	44.1%	45.7%	49.0%
Second heating (1500° C)	CaO—	47.9%	50.4%	40.7%
	K_2O—	7.1%	3.0%	9.4%
	Al_2O_3—	45.0%	46.6%	49.9%
Third heating (1500° C)	CaO—	48.4%	50.6%	40.9%
	K_2O—	6.4%	2.5%	9.1%
	Al_2O_3—	45.2%	46.9%	50.0%

In Table III there is given a comparison of the ratios of $CaO:K_2O:Al_2O_3$ in a sample heated at 1500° C., as determined by analysis and by direct weighing.

TABLE III.

Component	Ratio of Oxides by Analysis	Ratio of Oxides by Direct Weighing
CaO	47.7	47.6
K_2O	14.0	13.5
Al_2O_3	38.3	38.9

More than seventy-five different compositions were studied within the region of the diagram indicated in Fig. 2. Fifty of these were in the portion of the system shown in the inset where the most detailed thermal studies were made.

The samples were finely ground and portions of about 0.3 gram were taken for determining the temperature relations in the system. Temperatures were measured with a platinum-platinum-rhodium thermocouple and a Leeds and Northup potentiometer.

Heating curves were not employed for the determination of the melting temperatures, for thermo-elements in contact with melt containing potash are readily attacked. Temperature determinations made by this method would be unreliable. Accordingly, the quenching method was used exclusively for the determination of the temperature relations. In the quenching method a small portion of the sample was enclosed in platinum foil. This charge was suspended by a very fine platinum wire in the hot zone of an upright platinum resistance furnace (9), close to the junction of the thermocouple. The heating element of the furnace was 80% platinum—20% rhodium wire. Temperatures of 1700° C. could be obtained. The temperature of the furnace was controlled by means of a Robert's regulator (10).

The charges which were used for the final determination of the temperature relations were never held in the hot zone of the furnace for more than thirty minutes; but they were held at the temperature of study for about fifteen or twenty minutes. In establishing the equilibrium conditions in the system the time factor had to be taken into account. Accordingly, charges of the same sample were heated for varying periods; and in general it was found that a charge held at a definite temperature for fifteen to twenty minutes showed the same phases as another charge of the same composition held at the same temperature for longer periods, so that equilibrium was established within that time.

Following such heat treatment a heavy electric current was passed through the fine suspension wire, whereupon it fused and the charge dropped through an opening in the furnace into a reservoir of mercury where it was quenched. By means of petrographic and X-ray examination of the quenched material, the condition of the sample at the temperature of the furnace could be determined. Liquid appeared in the quenched sample as glass, while crystalline material remained unchanged.

Melting temperatures of the samples were determined in the following manner: A charge was heated at an arbitrary temperature and quenched. If no liquid was present at that temperature, that is if no glass was present in the quenched material, another charge of the same sample was heated at a higher temperature, quenched and examined. The temperature of heating was increased progressively until the sample at one temperature still contained crystalline material while at a temperature five degrees higher it was completely liquid. The mean value of these two determinations was taken as the melting temperature of the sample.

In order to assure equilibrium conditions in the samples, melting temperatures were also determined on samples cooled from higher temperatures when the deposition of crystals indicated the solidification point. In this way the condition of equilibrium was approached from two directions.

During the period of heating some potash was undoubtedly lost from the charges. The amount volatilized from the samples, which were always tightly wrapped in platinum foil, was so small that changes in the composition could not be detected. Thus, in working with samples lying close to the boundary between the fields of $5CaO.3Al_2O_3$ and $CaO.Al_2O_3$, the phase which crystallized primarily from charges of the same sample heated for periods varying from twenty minutes to one hour, was always $5CaO.3Al_2O_3$. Had the amount of K_2O lost been appreciable, the composition would have been shifted into the field of primary crystallization of $CaO.Al_2O_3$. Such irregularities were never noted along any of the boundary curves, hence evaporation loss was negligible.

Furthermore, thermal data showed that there was no general shift of the compositions of the samples towards the base line

$CaO-Al_2O_3$ due to appreciable loss of K_2O. Temperature determinations along the curve D-G, Fig. 2, indicated a maximum very close to the composition represented by point F. According to the phase rule this maximum must fall on the line connecting the compositions of the two phases crystallizing primarily on either side of the curve D-G; that is, the maximum must fall on the line connecting the compositions, $5CaO.3Al_2O_3$ and $K_2O.Al_2O_3$. If all of the compositions in the system were too low in K_2O, that is, shifted towards the base of the triangle, the direction of the line $5CaO.3Al_2O_3$-F would be towards some other composition than that of $K_2O.Al_2O_3$, which would be in conflict with other evidence.

After continued use of the furnace, an atmosphere of K_2O vapor was created in it which reacted slowly with the thermocouples. Accordingly, frequent calibration and correction of the elements was necessary. This was done by comparison with a standard thermocouple; and by checking the melting points of the compounds and eutectics in the $CaO-Al_2O_3$ system.

More than three hundred heat treatments and microscopic examinations were made on the seventy-five compositions selected progressively to define the boundary curves and to obtain the temperature relations in the system. The relevant values are submitted with a critical analysis and interpretation of the results.

THE BINARY SYSTEMS OF THE COMPONENTS.

The System $CaO-K_2O$.—No evidence was obtained of the existence of any compounds of CaO and K_2O. At temperatures up to 1550° C. there was no liquid formation and the samples quenched or cooled from that temperature contained only one phase, CaO, having grains of normal appearance and refractive index. The potash appeared to have been almost completely volatilized; solid solution was not observed.

The System $CaO-Al_2O_3$.—This system was studied by Rankin and Wright. The detailed relations in the system are given in their paper: "The Ternary System $CaO-Al_2O_3-SiO_2$" (1).

The System $K_2O-Al_2O_3$.—The system $K_2O-Al_2O_3$ was not investigated completely because of the extremely high temperatures which fall out of the range of the thermocouples. Eight compositions were studied in the system. No melting occurred in these preparations when heated to 1600° C., hence the temperatures of melting of the eutectics and compounds could not be determined. Microscopic examination of the heated preparations showed the presence of two phases, $K_2O.Al_2O_3$ and β-Al_2O_3. When a preparation of the composition $K_2O + Al_2O_3$ was heated to 1650° C. only one phase persisted; this indicates that no observable dissociation of the compound $K_2O.Al_2O_3$ occurs at that temperature. It appears from these observations that $K_2O.Al_2O_3$ is the only compound of potash and alumina in this system. The compound contains 48.06% K_2O and 51.94% Al_2O_3.

The optical properties and the X-ray diffraction pattern of the compound $K_2O.Al_2O_3$ were measured. It crystallizes in the isometric system. The refractive index of the compound is 1.603 ± .005 for artificial white light. In unmelted samples in the binary system the grains were colorless and rounded; occasionally in melts in the ternary system $K_2O.Al_2O_3$ was found to crystallize as perfect octahedrons.

$K_2O.Al_2O_3$ is extremely hygroscopic and, therefore, it was necessary to grind it in a hot mortar prior to microscopic and X-ray examination. The interplanar spacings of the X-ray diffraction pattern are given in Table IV. The radius of the cassettes was eight inches and the effective wave length of the X-rays was 0.712 A. U.

TABLE IV.

Interplanar Spacings of $K_2O.Al_2O_3$.

Line No.	d_{hkl}	Intensity
1	3.07	ww
2	2.72	ss
3	2.59	w
4	2.48	w
5	2.395	w
6	2.315	m
7	2.215	w
8	2.000	w
9	1.918	m
10	1.567	s
11	1.488	ww
12	1.348	m
13	1.214	s
14	1.109	w
15	1.025	m
16	.906	w
17	.860	w
18	.820	w
19	.754	w

ss, very strong; s, strong; m, medium; w, weak; ww, very weak

When samples of Al_2O_3 containing 3.5 per cent K_2O were heated to 1550° C., corundum and β-Al_2O_3 crystallized. The latter phase was highly birefracting and had a platy crystal habit. The individual crystals were too small and intergrown to make accurate index determinations; however, the mean refractive index of masses of these crystals was 1.663. All of these properties correspond to those of other samples of β-Al_2O_3 examined.

THE TERNARY SYSTEM.

No ternary compounds of CaO, K_2O and Al_2O_3 were found in equilibrium with liquid in the region of the system studied. The products of final crystallization from melts in the system are shown in Fig. 1.

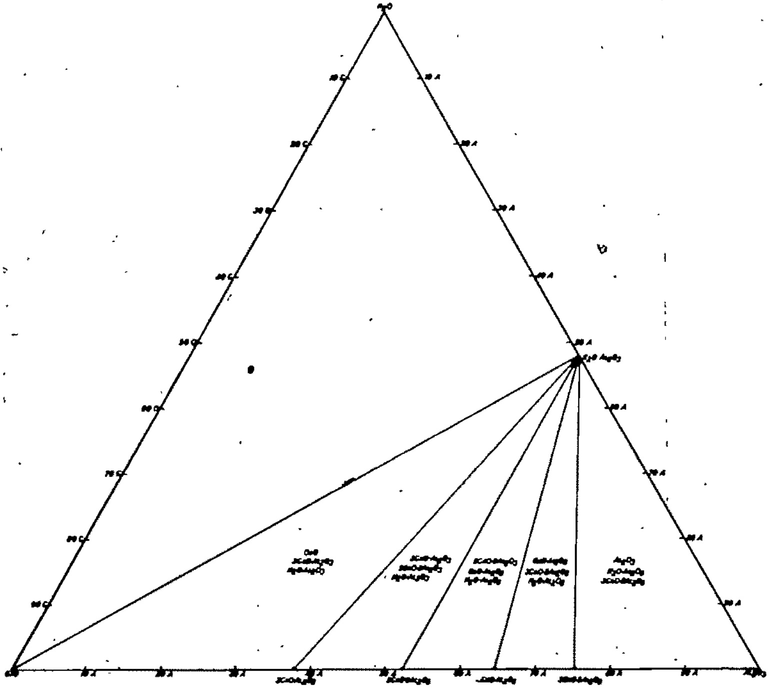


Fig. 1. Diagram showing the final products of crystallization from melt in the ternary system CaO-K_2O-Al_2O_3.

THE STABILITY FIELDS.

The fields of stability of the various compounds in the ternary diagram are shown in Fig. 2.* Each of the components CaO and Al_2O_3, as well as $K_2O.Al_2O_3$, and the binary compounds of CaO and Al_2O_3, are in equilibrium with liquid in the system.

The compound $5CaO.3Al_2O_3$ does not crystallize as such in the ternary system, but as a solid solution of K_2O in $5CaO.3Al_2O_3$. The index of refraction of this solid solution varies in accordance with the amount of K_2O dissolved. When the maximum amount of K_2O is present (about 2%) the index of refraction of the phase is 1.593; the refractive index of pure $5CaO.3Al_2O_3$ is 1.608. The X-ray diffraction pattern

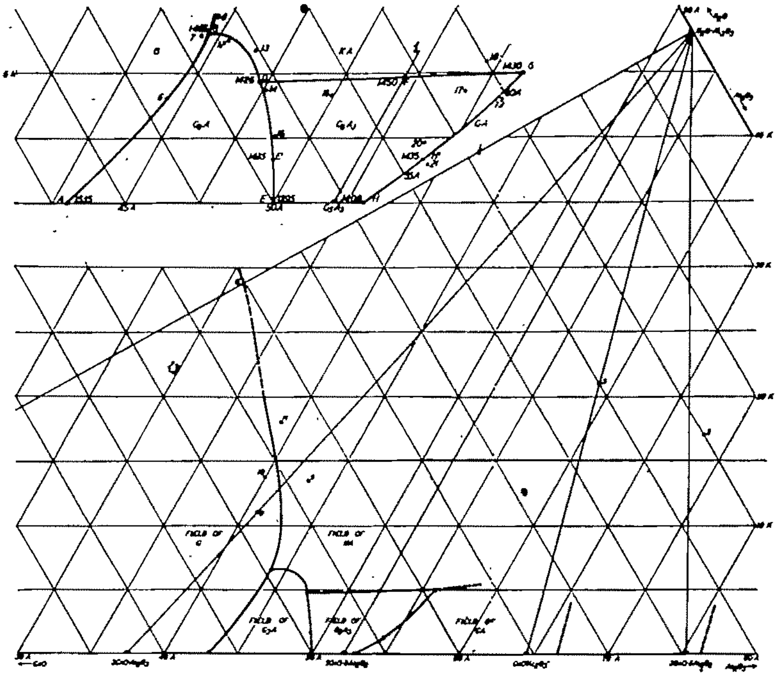


Fig. 2. Diagram showing the fields of primary crystallization and binary systems within the ternary system $CaO-K_2O-Al_2O_3$.

---

* For convenience, an abbreviated form of writing the compositions of compounds has been used. Accordingly, for K_2O the symbol "K" is used; for CaO "C"; and for Al_2O_3 "A." Thus $KA = K_2O.Al_2O_3$, $C_3A = 3CaO.Al_2O_3$, $C = CaO$. An enlarged portion of the principal fields is shown separately in the diagram.

of the solid solution shows a regular shift in the lines of the pattern as K_2O is progressively taken into solution.

Because of the similarity in optical properties of $K_2O.Al_2O_3$ and $5CaO.3Al_2O_3$ (+ K_2O), some difficulty was encountered in allocating the boundary curve between the fields of primary crystallization of these phases. Both compounds are isotropic and have indices of refraction differing by only 0.01. When $K_2O.Al_2O_3$ crystallizes as the primary phase it forms rounded grains with regular outline; on the other hand, $5CaO.3Al_2O_3$ (+ K_2O) has never been observed to crystallize in this form from melt, but only as irregular grains with jagged edges. This difference in crystallization habit of the phases served as a convenient means for differentiating them. For the final location of the boundary curve, however, samples 13 and 14, Fig. 2, were quenched from temperatures at which only one crystalline phase remained in the glass. These samples were X-rayed and their diffraction patterns were distinctly different; that of sample 13 corresponded to the pattern of $K_2O.Al_2O_3$ and that of sample 14 to $5CaO.3Al_2O_3$ (+ K_2O).

Although the field of primary crystallization of $K_2O.Al_2O_3$ was not completely outlined, samples examined over the greater portion of the system showed that its field of stability adjoins the fields of other compounds in the system. In Table V are given the results of an examination of samples which were studied to substantiate this statement.

TABLE V.

Melting Temperatures in the Field of $K_2O.Al_2O_3$.

	Composition			Heat		
Sample	CaO	K_2O	Al_2O_3	Treatment		Examination
1	19.0	39.0	42.0	1550	Cooled	KA, Glass
2	15.0	17.0	68.0	1655	Quenched	KA, Glass
				1655	Cooled	KA, C_5A_3
3	20.0	21.0	59.0	1530	Quenched	KA, Glass
				1530	Cooled	KA, CA
4	42.2	6.3	51.5	1455	Quenched	KA, Glass
				1455	Cooled	KA, C_5A_3, Glass
5	43.3	13.5	43.0	1480	Quenched	KA, C_3A, C, Glass
				1490	Quenched	KA, C, Glass

In the region of primary crystallization of $3CaO.Al_2O_3$, that compound crystallized as well-developed polyhedrons usually with octagonal outline. By careful heat treatment and quenching from a suitable temperature it was possible to isolate extremely large, perfect crystals of $3CaO.Al_2O_3$. Fig. 3 shows a photograph of one of these crystals imbedded in glass. The crystal was approximately 200 microns long; it showed no birefringence and appears to be a combination of the cube, octahedron and dodecahedron.

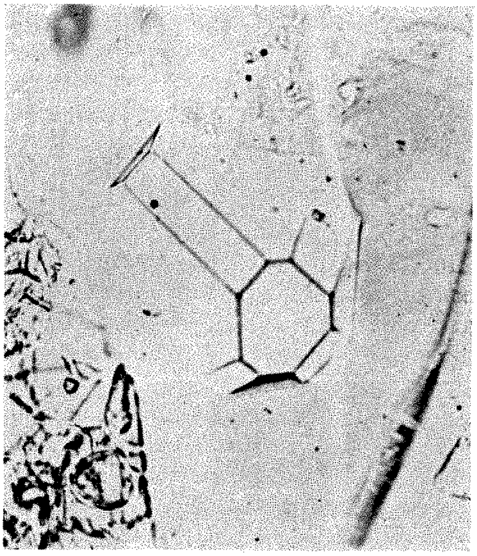


Fig. 3. Photomicrograph of crystal of $3CaO.Al_2O_3$ in glass. Actual length 200 μ.

In other regions of the diagram crystal development of the calcium aluminates from melt was extremely good; apparently the viscosity of the melts containing K_2O was favorable for the formation of crystals with well-developed faces.

THE QUINTUPLE POINTS

Two quintuple invariant points were found in the system which represent ternary eutectics; that is, invariant compositions at which three solid phases may co-exist with liquid and vapor. These are points D and G.

Point D is the eutectic for $5CaO.3Al_2O_3$ $(+K_2O)$, $3CaO.Al_2O_3$ and $K_2O.Al_2O_3$. It occurs at the composition 48.0 per cent CaO, 4.8 per cent K_2O and 47.2 per cent Al_2O_3. It melts at 1425° ± 5° C.

Point G is the eutectic point for $5CaO.3Al_2O_3$ (+ K_2O), $CaO.Al_2O_3$ and $K_2O.Al_2O_3$. It occurs at the composition 39 per cent CaO, 5 per cent K_2O and 56 per cent Al_2O_3. It melts at 1430° ± 5° C.

One quintuple invariant point B was found in the system which was not a eutectic; that is, an invariant composition at which three solid phases may exist with liquid and vapor but which lies outside the triangle formed by the lines joining the compositions of the three solid phases. It occurs at the composition 48.8 per cent CaO, 6.5 per cent K_2O and 44.7 per cent Al_2O_3 and melts at 1475° ± 5° C. At this point $3CaO.Al_2O_3$, CaO and $K_2O.Al_2O_3$ exist in contact with liquid and vapor.

THE BOUNDARY-CURVES.

The compositions limiting the field of primary crystallization of CaO are represented in the diagram, Fig. 2, by the curve A-B-C. The melting temperatures of the compositions represented by this curve decrease from 1535° C. at composition A to 1485° C. at composition B, which is the quintuple invariant composition of $3CaO.Al_2O_3$, CaO and $K_2O.Al_2O_3$. The dotted portion of this curve, B-C, was not accurately located because of the high temperatures involved. However, the experimental data indicate that the melting temperatures are increasing from composition B to a maximum on the binary system CaO-$K_2O.Al_2O_3$ in the vicinity of composition C, Fig. 2. The melting relations of the compositions along curve A-B-C are given in detail in Table VI.

TABLE VI.

Melting Temperatures Along the Boundary Curve Separating the Fields of CaO and $K_2O.Al_2O_3$.

Sample	Composition CaO	Composition K_2O	Composition Al_2O_3	Heat Treatment		Examination
		Per cent				
6	52.0	4.0	44.0	1495	Quenched	C_3A, C, Glass
				1505	Quenched	Glass
7	49.5	6.5	44.0	1475	Quenched	C_3A, C, KA, Glass
				1485	Quenched	C, Glass
8	48.0	8.0	44.0	1500	Quenched	C, KA, Glass
				1508	Quenched	KA, Glass
9	48.0	11.0	41.0	1583	Quenched	C, KA, Glass
				1593	Quenched	C, Glass
10	47.0	14.0	39.0	1625	Quenched	C, KA, Glass
				1635	Quenched	C, Glass
11	43.0	18.0	39.0	1665	Quenched	C, KA, Glass

In Table VII are given experimental determinations which indicate the limiting compositions separating the field of primary crystallization of $3CaO.Al_2O_3$ from that of $K_2O.Al_2O_3$, represented by curve B-D. The data show that the melting temperatures along this part of the curve decrease regularly from 1485° C. at composition B to 1425° C. at composition D, which is the ternary eutectic of $3CaO.Al_2O_3$, $K_2O.Al_2O_3$ and $5CaO.3Al_2O_3(+ K_2O)$.

TABLE VII.

Melting Temperatures Along the Boundary Separating the Fields of $3CaO.Al_2O_3$ and $K_2O.Al_2O_3$.

Sample	Composition			Heat Treatment		Examination
	CaO	K_2O	Al_2O_3			
		Per cent				
7	49.5	6.5	44.0	1475	Quenched	C_3A, KA, C, Glass
				1485	Quenched	C, Glass
12	48.5	6.4	45.1	1460	Quenched	C_3A, KA, Glass
				1470	Quenched	C_3A Glass
13	47.0	6.0	47.0	1420	Quenched	Not sintered
				1430	Quenched	Melting begun
				1450	Quenched	C_3A, KA, Glass
				1455	Quenched	KA, Glass
14	47.9	4.5	47.6	1420	Quenched	No melting
				1430	Quenched	Melting begun
				1435	Quenched	Glass

In Table VIII are given data which indicate the thermal relations of the compositions separating the fields of primary crystallization of $3CaO.Al_2O_3$ and $5CaO.3Al_2O_3$, curve D-E. The melting temperatures of the compositions increase from 1425° C. at composition D, the ternary eutectic, to a maximum of 1435° C. at composition E′ along the curve; from composition E′ the melting temperatures again decrease to 1395° C., the melting point of the binary eutectic of $3CaO.Al_2O_3$ and $5CaO.3Al_2O_3$. Thus the ternary eutectic D melts at a higher temperature than the binary eutectic E. This may appear to be a contradiction of the theorem of van Alkemade, from whose deductions "it is known that the temperatures fall along the sides of the triangle towards the ternary eutectic" (11).

These results have been interpreted in the following manner: Pure $5CaO.3Al_2O_3$ does not exist in this ternary system but takes up K_2O in solid solution. Hence there are only two phases taking part in the equilibrium until the solid solution of K_2O in $5CaO.Al_2O_3$ attains saturation. Therefore, the binary eutectic to be considered in this case is not one of $3CaO.Al_2O_3$ with pure $5CaO.3Al_2O_3$ but one of $3CaO.Al_2O_3$ with $5CaO.3Al_2O_3(+K_2O)$ with a melting point of 1435° C.; accordingly the temperatures fall from the binary eutectic to the ternary eutectic in agreement with van Alkemade's theorem.

Table VIII.

Melting Temperatures Along the Boundary Curve Separating the Fields of $3CaO.Al_2O_3$ and $5CaO.3Al_2O_3$.

Sample	Composition			Heat Treatment		Examination
	CaO	K_2O	Al_2O_3			
		Per cent				
14	47.9	4.5	47.6	1420	Quenched	No melting
				1430	Quenched	Melting begun
				1435	Quenched	Glass
15	48.7	2.5	48.8	1438	Quenched	C_3A, C_5A_3, Glass
				1447	Quenched	Glass

The temperature relations of the compositions separating the fields of primary crystallization of $5CaO.3Al_2O_3(+K_2O)$ and $K_2O.Al_2O_3$, represented by curves D-G which are given in Table IX. There is a maximum melting temperature along this curve at composition F, the eutectic of $5CaO.3Al_2O_3(+K_2O)$ and $K_2O.Al_2O_3$. This binary eutectic melts at 1450° C. ± 5° C. From composition F the melting temperatures decrease along the curve to 1430° ± 5° C. at composition G, the ternary eutectic of $5CaO.3Al_2O_3(+K_2O)$, $CaO.Al_2O_3$ and $K_2O.Al_2O_3$.

Table IX.

Melting Temperatures Along the Boundary Curve Separating the Fields of $5CaO.3Al_2O_3$ and $K_2O.Al_2O_3$.

Sample	Composition			Heat Treatment		Examination
	CaO	K_2O	Al_2O_3			
		Per cent				
14	47.9	4.5	47.6	1420	Quenched	Not sintered
				1430	Quenched	Melting begun
				1435	Quenched	Glass
16	46.0	4.3	49.7	1420	Quenched	No melting
				1430	Quenched	C_5A_3, Glass
4	42.2	6.3	51.5	1445	Quenched	C_5A_3, KA, Glass
				1455	Quenched	KA, Glass
17	42.0	4.0	54.0	1433	Quenched	C_5A_3, KA, Glass
				1450	Quenched	C_5A_3, Glass
18	40.0	5.5	54.5	1430	Quenched	C_5A_3, KA, Glass
				1435	Quenched	Glass

In Table X there are given the data showing the melting temperatures of the compositions limiting the fields of primary crystallization of $5CaO.3Al_2O_3(+K_2O)$ and $K_2O.Al_2O_3$, curve G-H. The melting temperature of the ternary eutectic G is 1430° ± 5° C., while that of the binary eutectic of $5CaO.3Al_2O_3$ and $CaO.Al_2O_3$, composition H, is 1400° ± 5° C. The relations along this boundary curve are similar to those along B-E. That is, a maximum melting point occurs along the curve G-H at composition H′. H′ must be considered as the binary eutectic in this case since the solid solution K_2O in $5CaO.3Al_2O_3$ only attains saturation at this composition and, therefore, only two phases take part in the equilibrium. The melting temperature of composition H′ is 1435° ± 5° C.

TABLE X.

Melting Temperatures Along the Boundary Curve Separating the Fields of $5CaO.3Al_2O_3$ and $CaO.Al_2O_3$.

Sample	Composition CaO	 K_2O	 Al_2O_3	Heat Treatment		Examination
		Per cent				
19	40.3	4.0	55.7	1422	Quenched	No melting
				1430	Quenched	Melting begun
				1438	Quenched	CA, Glass
				1445	Quenched	Glass
20	44.0	2.0	54.0	1430	Quenched	C_5A_3, CA, Glass
				1440	Quenched	C_5A_3, Glass
21	44.5	1.0	54.5	1447	Quenched	C_5A_3, CA, Glass
				1455	Quenched	CA, Glass

THE BINARY SYSTEMS WITHIN THE TERNARY DIAGRAM.

The system CaO-$K_2O.Al_2O_3$.—Since the line joining the compositions of the two compounds lies wholly within the fields of primary crystallization, the compounds form a true binary system with a eutectic in the vicinity of point C. Mixtures of the two compounds in varying proportions were heated to 1700°; CaO and $K_2O.Al_2O_3$ were identified microscopically.

The system $3CaO.Al_2O_3$-$K_2O.Al_2O_3$.—The line connecting the compositions of the two compounds does not lie entirely within the fields of primary crystallization, so that the compounds do not form a true binary system. $3CaO.Al_2O_3$ does not appear on the liquidus of the system.

The system $5CaO.3Al_2O_3$-$K_2O.Al_2O_3$.—The compounds form a true binary system with a eutectic at the percentage composition CaO 42.5, K_2O 5.0, Al_2O_3 52.5. The melting temperature of the eutectic is 1450° ± 5°.

The system $CaO.Al_2O_3$-$K_2O.Al_2O_3$.—$CaO.Al_2O_3$ and $K_2O.Al_2O_3$ were identified in mixtures in the binary system $CaO.Al_2O_3$-$K_2O.Al_2O_3$ heated to 1600° ± 5°. The melting temperature of the eutectic was not determined.

The system $3CaO.5Al_2O_3$-$K_2O.Al_2O_3$.—$3CaO.5Al_2O_3$ and $K_2O.Al_2O_3$ were identified in mixtures in the binary system $3CaO.5Al_2O_3$-$K_2O.Al_2O_3$ heated to 1600° ± 5°. The melting temperature of the eutectic was not determined.

SUMMARY.

A detailed investigation of a portion of the system CaO-K_2O-Al_2O_3 has been reported. The conditions of equilibrium in mixtures of these oxides were established from thermal and optical studies.

The compound $K_2O.Al_2O_3$ was synthesized and its optical properties and X-ray diffraction pattern were measured. It crystallizes in the isometric system. The index of refraction of the compound is 1.603 ± 0.003.

The compound $K_2O.Al_2O_3$ is the only compound of K_2O which exists in equilibrium with liquid in the system. Accordingly that compound will crystallize from melt in all portions of the diagram which were studied.

β-Al_2O_3 was found to crystallize in the binary system K_2O-Al_2O_3.

Detailed thermal data are included for the regions of stability in the system of $3CaO.Al_2O_3$, $5CaO.3Al_2O_3$ and portions of the fields of $K_2O.Al_2O_3$ and CaO. The compounds and invariant points of the system are set down in Table XI.

TABLE XI.

Compounds and Invariant Points.

	Composition				
	CaO	Al_2O_3 Per cent	K_2O	Melting Point	Authority
Binary Compounds					
C_3A	62.22	37.78		Dissociates to CaO and liquid at 1535°	Rankin et al.
C_5A_3	47.78	52.22		1455°	Rankin et al.
CA	35.44	64.56		1600°	Rankin et al.
C_3A_5	24.78	75.22		1720°	Rankin et al.
KA		51.94	48.06	Above 1650°	Brownmiller
Binary eutectics					
C_3A-C_5A_3	50.00	50.00		1395°	Rankin et al.
C_5A_3-CA	47.00	53.00		1400°	Rankin et al.
CA-C_3A_5	33.50	66.50		1590°	Rankin et al.
Quadruple point not a eutectic					
CaO-C_3A	57.00	43.00		1535°	Rankin et al.
Ternary eutectics					
C_3A-KA-C_5A_3	48.0	47.2	4.8	1425°	Brownmiller
CA-C_5A_3-KA	39.0	56.0	5.0	1430°	Brownmiller
Quintuple point not a eutectic					
CaO-C_3A-KA	48.8	44.7	6.5	1485°	Brownmiller

ACKNOWLEDGMENTS.

The author wishes to express his gratitude to Professor L. T. Work, under whose guidance and direction the work was performed, for the helpful and sympathetic assistance and advice which he contributed during the course of the investigation.

The author is deeply grateful to the late Dr. S. A. Goldschmidt, the donor of the Fellowship in Columbia University which the author held during the period of the investigation.

The author wishes to express his appreciation to Dr. D. D. Jackson for his interest in the work and his willingness to assist in the arrangements for carrying out the project; and to Dr. R. H. Bogue for his coöperation and for his permission to use the facilities of the Portland Cement Association Laboratory at the Bureau of Standards for completing some of the experimental work.

BIBLIOGRAPHY.

1. Rankin and Wright: This Journal, 39, 1, 1915.
2. Publications from Geophysical Laboratory, Washington.
3. Hansen and Bogue: J. Amer. Chem. Soc., 48, 1261, 1926.
4. Hansen, Brownmiller and Bogue: J. Amer. Chem. Soc., 50, 396, 1928.
5. Hansen and Brownmiller: This Journal, 15, 225, 1928.
6. Hansen: J. Amer. Chem. Soc., 50, 3081, 1928.
7. Brownmiller and Bogue: This Journal, 23, 501, 1932; Bureau Standards J. Research, 8, 414, 1932.
8. Morgan: Dissertation, Columbia Univ., 1919.
9. Shepherd, Rankin and Wright: This Journal, 28, 308, 1909.
10. Adams: J. Optical Soc. Am., 9, 599, 1924.
11. van Alkemade, Geer: J. Phys. Chem., 8, 259, 1904; Bancroft, The Phase Rule, p. 149.

HARTSDALE,
NEW YORK.

PRE-CAMBRIAN GRANITES OF THE BLACK HILLS.

GARVIN L. TAYLOR.

ABSTRACT.

Pre-Cambrian granites of the Black Hills were studied to determine the number of granites present; the conclusion reached is that there are at least two within the area. The laboratory methods used for differentiating and correlating the granites were the determination of the lead-uranium ratios of zircons occurring in the heavy concentrates, and the examination of the heavy minerals both with the petrographic microscope and with the spectrograph.

GENERAL PRE-CAMBRIAN GEOLOGY OF THE BLACK HILLS.

The pre-Cambrian core of the Black Hills, as exposed, consists of relatively thick systems of sedimentary rocks which have been highly metamorphosed and have been highly intruded by at least two types of igneous rocks of pre-Cambrian age. The three systems of sedimentary rocks, in chronological order, are the Nemo, the Estes, and the Lead.[1] The sedimentary rocks of the southern Black Hills are believed to belong to the Estes system (see map) and the Lead system, and possibly to a younger system which outcrops northwest of Custer. The igneous rocks are granites, closely associated pegmatites, and amphibolites. The granites are very widespread in occurrence throughout the southern part of the Black Hills but are exposed in only a few places in the northern part.

THE GRANITES.

GENERAL STATEMENT.

The Black Hills pre-Cambrian granites of the Harney Peak district have been described by Van Hise,[2] Ziegler,[3] and Paige,[4] and their structure and mode of intrusion by Paige,[5] Runner,[6]

---

[1] Runner, J. J.: Pre-Cambrian Geology of the Nemo District, Black Hills, S. D. This Journal, November, 1934.

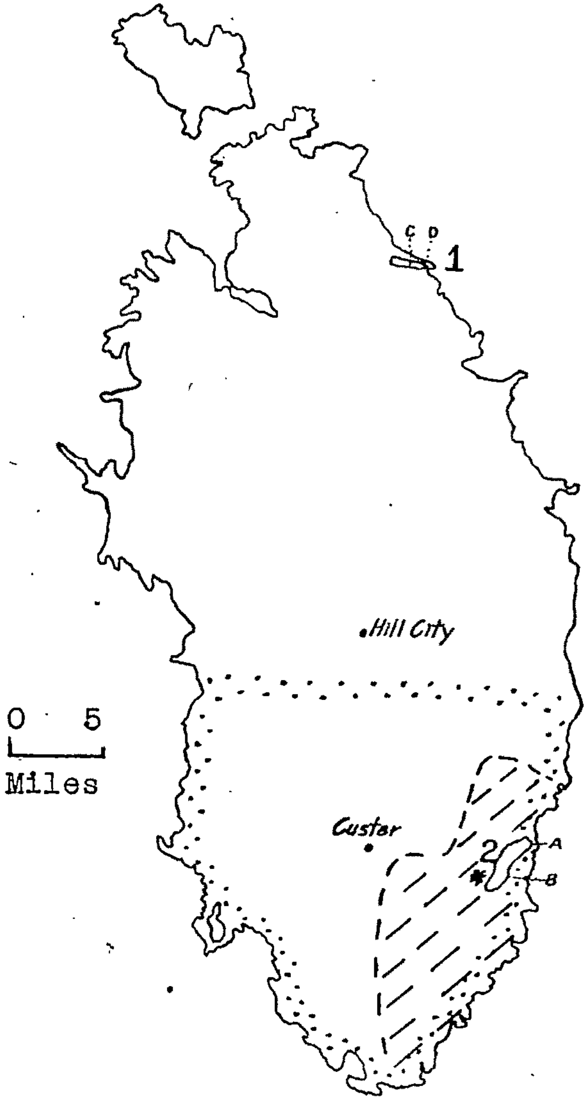
[2] Van Hise, C. R.: The Pre-Cambrian Rocks of the Black Hills. Geol. Soc. Amer. Bull., vol. 1, pp. 203-245, 1890.

[3] Ziegler, Victor: The Differentiation of a Granitic Magma as Shown by the Paragenesis of the Minerals of the Harney Peak Region, S. D. Econ. Geol., vol. 9, p. 270, 1914.

[4] Darton, N. H., and Paige, Sidney: Central Black Hills Folio, S. D. U. S. Geol. Survey, Geol. Atlas, Folio 219, 1925.

[5] Ibid.

[6] Runner, J. J.: Intrusion Mechanics of the Harney Peak Batholithic Granite. Geol. Soc. Amer. Bull., vol. 39, p. 186, 1928.



Map Showing Pre-Cambrian Outcrops in the Black Hills.

Area enclosed within the dotted lines is that in which the Harney Peak "fine-grained" granite is exposed.

Estes (?) system, cross-hatched.

1. Little Elk gneissoid granite.
2. Game Lodge granite.

A. Location of sample no. A. of Game Lodge granite.
B. Location of sample no. B. of Game Lodge granite.
C. Location of sample no. C. of Little Elk gneissoid granite.
D. Location of sample no. D. of Little Elk gneissoid granite.
* Location of sample of Harney Peak "fine-grained" granite.

and Balk.[7] None of these writers has described granites belonging to different magmatic periods, but Ziegler, Paige, and Runner have recognized that the intrusions of the various masses were not simultaneous.

In the valley of Galena Creek (see map), west of the Game Lodge Hotel is exposed a dull gray, fine-grained, foliated biotite-granite which will be referred to in this paper as the Game Lodge granite.

The rocks mapped as "granite and pegmatite" by Paige[8] have been called the Harney Peak granite by several writers. This term includes both the granitic and pegmatitic facies of the intrusive. The pegmatitic facies of a granite frequently differs widely from the granitic facies in composition and texture. Hence if the Game Lodge granite or other granites are to be compared with the Harney Peak granite, they should be compared with like facies of the latter. For this reason the author did not include the pegmatites of the Harney Peak granite in this study. Within the area mapped by Paige as "granite and pegmatite" are found masses of a "fine-grained", white to gray granite. This granitic facies is regarded as derived from the parent magma before magmatic differentiation to form pegmatites had been completed, and it is, therefore, older than the pegmatites. The pegmatitic facies were observed to be, in all but a few places, coarser-grained than the "fine-grained" white to gray granitic facies. The pegmatitic facies cut the "fine-grained" white to gray granitic facies in every large exposure of the latter observed. In many cases the number of pegmatitic dikes in a single exposure of the granitic facies is very great, making it impossible to obtain samples which would be representative of either. In this paper the term Harney Peak "fine-grained" granite includes only the finer-grained white to gray granitic facies, whereas the term Harney Peak granite as used by other writers includes all facies of this granitic mass.

In the northern Black Hills in the valley of Little Elk Creek (see map), a medium-grained gneissoid granite is exposed which will hereafter be referred to as the Little Elk gneissoid granite.

---

[7] Balk, Robert: Inclusions and Foliation of the Harney Peak Granite, S. D. Jour. Geol., vol. 49, p. 736, 1931.

[8] Darton, N. H., and Paige, Sidney: op. cit., Areal Geology.

GAME LODGE GRANITE.

The Game Lodge granite exposed near the Game Lodge Hotel has not been previously described in geologic literature, but has been known for several years.[9] It occurs as intrusive masses into pre-Cambrian sediments which, according to Dr. J. J. Runner,[10] are believed to be the equivalent of the Estes system. Pebbles resembling this granite occur in a younger pre-Cambrian conglomerate which is believed to belong to the Lead system or perhaps to a younger system. The Game Lodge granite is cut by dikes of the Harney Peak "fine-grained" granite and pegmatites.

The Game Lodge granite is a fine-grained (crystals 1 mm. to 3 mm. dia.), gray biotite-granite which consists essentially of quartz, feldspars, and biotite. It is more compact and darker than most of the Harney Peak granite. It has a hypautomorphic-equigranular texture with a plane and linear parallel structure due to the orientation of the biotite, and, to a lesser extent, of the oligoclase.

Oligoclase (approximately An_{20}) is one of the major constituents of this granite. It shows Carlsbad, albite, and pericline twinning and has been partially replaced by muscovite, epidote-clinozoisite, calcite, quartz, albite, and microcline. Surrounding the oligoclase is frequently a very thin border zone of more alkalic feldspar which, in some cases, contains myrmekite-like structures. Quartz, albite, and microcline are abundant and occur as fractured but unaltered grains. In places these minerals enclose small grains of oligoclase poikiloblasticly. Biotite of two generations occurs in this granite. The older biotite is orientated with the oligoclase. In some places it has changed from a brown to a green color, and in other places it has changed to chlorite or epidote-clinozoisite. Very small amounts of a younger biotite occur with muscovite in fracture zones cutting the feldspars. Nearly colorless zircons commonly occur as inclusions in biotite and feldspar. Minor quantities of orthoclase, microperthite, titanite, pyrrhotite, apatite, and magnetite are also present.

Interesting reaction rims occur around minerals enclosed in biotite and oligoclase. In some cases the minerals appear to have the properties of zircon. The rims consist of two bands, in both of which the minerals are so small that they were not identified. The outer band is anisotropic with a brownish-green color. The inner band is usually nearly isotropic and is lighter in color than the outer band. In some cases the core mineral has an index of about 1.63. When in biotite, the entire structure is surrounded by haloes which are the same size as those surrounding the known zircons. This fact suggests that the reaction rims are alteration products of a radioactive mineral. This reaction rim structure was not observed in either the Harney Peak "fine-grained" granite or the Little Elk gneissoid granite.

---

[9] Runner, J. J.: Personal communication.

[10] Ibid.

The first major constituents to crystallize were biotite and oligoclase which were probably orientated by differential pressure to give the plane and linear structure of the rock. Albite, microcline, and quartz formed later, and partially replaced the oligoclase. After these minerals had crystallized, fractures were developed in which muscovite and a little biotite formed. At some time epidote-clinozoisite, calcite, and chlorite formed. If the small amount of muscovite present had been introduced by the Harney Peak granitic magma, it seems likely that some tourmaline would also have been introduced.

HARNEY PEAK "FINE-GRAINED" GRANITE.

The Harney Peak "fine-grained" granite is white to gray in color, is composed of crystals 2 mm. to 10 mm. in diameter, and has a hypautomorphic-equigranular texture. Locally it is banded due to segregation of minerals into layers. This granite consists essentially of quartz, alkalic feldspars, muscovite, tourmaline, and garnet. It is easily distinguished from the Game Lodge granite and the Little Elk gneissoid granite by its lighter color, its coarser texture, and its different mineralogy.

Quartz, microcline, and albite are very abundant in this granite. The larger quartz grains show a great deal of fracturing and undulatory extinction. In a few places the large fractured grains of microcline, albite, and orthoclase have been partly altered to muscovite. Some of the orthoclase has been replaced by microcline. Albite has replaced some of the microcline and in places has recrystallized to a younger albite. The author believes most of the garnet to be a primary mineral of this granite, since it is difficult to explain the widespread distribution of the mineral if it were obtained by assimilation of sediments. The garnets are subhedral to anhedral in form and have been extensively altered. They differ from the garnets which can be definitely traced into xenoliths and which are believed to be assimilation products in that the latter garnets are larger, euhedral, and less altered. Tourmaline and muscovite were present in all exposures studied. Some exposures contained as much as 15% tourmaline and others as much as 20% muscovite. Most of the tourmaline belongs to the schorlite and elbaite varieties. Zoned tourmaline is very common. A small amount of muscovite occurs as an alteration product of the feldspars. Zircon occurs in the feldspars, biotite, and tourmaline. It is light blue to colorless in thin sections. Magnetite, pyrite, pyrrhotite, biotite, beryl, and apatite occur in small quantities in this granite. Cassiterite was found abundantly in thin sections of granites which the author believes may perhaps more properly belong either to the pegmatitic facies of the Harney Peak granite or to the Harney Peak "fine-grained" granite where it has been contaminated by introduction of vein material.

Garnet, feldspars, and quartz were among the first essential minerals to form. After the crystallization of these minerals, cataclastic texture was developed, and then the tourmaline and muscovite crystallized.

LITTLE ELK GNEISSOID GRANITE.

The Little Elk gneissoid granite intruded pre-Cambrian sediments, but no field evidence was discovered which would indicate the relative ages of this granite and the Game Lodge granite, the Harney Peak "fine-grained" granite, or the igneous amphibolites. It is a light gray gneissoid granite composed of crystals 1 mm. to 10 mm. in diameter. The essential minerals are quartz, feldspars, and biotite. The gneissoid structure is due to the parallel arrangement of biotite layers in the sheared zones.

The Little Elk gneissoid granite has a hypautomorphic-equigranular texture in the more massive parts. Cataclastic texture is exhibited where the large grains of quartz and feldspar have been fractured, and where, in numerous places, all of the minerals have been crushed until only a mylonitic zone of small grains remains. Following some of the fractures, cutting feldspar especially, are veinlets of quartz, calcite, and muscovite. Foliated micaceous layers which occur in the mylonitic zones are composed essentially of biotite and muscovite, but also contain titanite, calcite, and epidote-clinozoisite. All of the minerals of these foliated layers are stained by yellow-brown iron oxides.

Quartz of this granite is believed to be of two ages. The older quartz occurs as large crystals showing undulatory extinction. The younger quartz occurs in the mylonitic zones and in the veinlets filling the fractures in the feldspars and older quartz. The feldspars, which occur chiefly as large grains, are, in the order of their abundance, albite (An_{10}), microcline, perthite, and orthoclase. Before the fracturing occurred, a large part of the orthoclase had been changed to microcline, and microcline had been in many grains wholly or partially replaced by albite. Some of the feldspar grains have been replaced in part by muscovite. Most of the biotite occurring in the irregular bands in the mylonitic zones is greenish-brown in color. Zircon occurs in the biotite and in the feldspars. It is usually colorless, but sometimes has a faint yellowish color. It differs from the zircon of the other two granites in that most of it exhibits a zoned structure. Epidote-clinozoisite, apatite, chlorite, titanite, pyrite, pyrrhotite, and magnetite are also present in this granite. Tourmaline was found in a vein which cuts this granite. It is thought that this vein is closely associated with the magma from which this granite was formed.

The quartz and feldspar which now occur as large fractured grains were among the first essential minerals to form. After the crystallization of these early minerals, the mylonitic zones and micaceous layers were formed and veinlets were developed along the fractures in the large quartz and feldspar grains. Whether or not material was added or removed from the granite at the time these changes took place or at a later time was not determined, but the presence of calcite-quartz-muscovite veinlets and the presence of considerable amounts of yellow-brown iron oxides in the micaceous layers perhaps indicate that some addition or removal of material might have occurred.

Correlation and Differentiation.

BY PETROGRAPHIC STUDY OF HEAVY MINERALS.

In gathering samples for heavy mineral analyses the author attempted at each outcrop to procure a fresh sample which would be truly representative of the granite at that place.

The light and heavy minerals were separated by means of a centrifuge and bromoform (G = 2.8).

The samples of the Harney Peak "fine-grained" granite studied were easily distinguished from those of the Game Lodge granite and the Little Elk gneissoid granite by a study of the heavy minerals. Tourmaline and garnet were found only in the Harney Peak "fine-grained" granite. Most of the zircons of this granite were light blue in color, whereas blue zircons were rarely found in the other two granites. In the Game Lodge granite and the Little Elk gneissoid granite, biotite constitutes 95% of the heavy minerals and titanite and epidote-clinozoisite are common, whereas in the Harney Peak "fine-grained" granite all of these minerals are uncommon. The Little Elk gneissoid granite differs from the Game Lodge granite in containing a larger per cent of green biotite, but this may be due to alteration. Most of the zircons observed in the Little Elk gneissoid granite were zoned, whereas zoned zircons were rarely found in the other granites.

TABLE 1.

Heavy Minerals.

Mineral	Harney Peak "Fine-Grained" Granite	Granite Game Lodge	Little Elk Gneissoid Granite
Apatite	p	abu	abu
Biotite			
Brown	p	95%	abu
Green	ni	abu	95%
Chlorite	ni	abu	abu
Clinozoisite	ni	abu	abu
Epidote	ni	p	p
Garnet	30%	ni	ni
Magnetite	p	p	p
Pyrite	p	ni	p
Pyrrhotite	p	p	p
Titanite	ni	abu	abu
Tourmaline	65%	ni	ni
Zircon			
Colorless	p	p	p
Colorless, zoned	p	p	abu
Blue	abu	ni	ni

abu—abundant but less than 1%
p—present
ni—not identified

BY SPECTRUM ANALYSES OF HEAVY MINERALS.

The correlation of the granites by spectrum analyses of the heavy minerals is based on the theory that the variations in the chemical compositions of the heavy minerals would be more noticeable than the variations in the total chemical compositions of the various granites.

Equal amounts of the heavy minerals concentrated by bromoform (G=2.7) were placed in platinum crucibles, treated with hydrofluoric and hydrochloric acids to remove the silica, dissolved in dilute hydrochloric acid, and concentrated to equal volumes. After that the procedure outlined by Popoff[11] was followed.

Owing to the great differences in iron, titanium, and magnesium, and the occurrence of some elements in only one granite, it was possible to distinguish between the spectra of the various concentrates without identifying any of the lines. By an examination of the individual lines of the spectra, however, differences in the percentage and occurrence of certain elements contained in the various samples could be detected. The heavy minerals of the Game Lodge granite and the Little Elk gneissoid granite which were analyzed contained a larger percentage of magnesium, iron, titanium, and zirconium than the like concentrates from the Harney Peak "fine-grained" granite. The specimens of the latter granite that were analyzed contained a larger percentage of potassium than either the Game Lodge granite or the Little Elk gneissoid granite. Concentrates from the Harney Peak "fine-grained" granite also contained elements not recognized in the other samples, namely, boron and lithium. The spectra of the Game Lodge granite and the Little Elk gneissoid granite resemble each other much more closely than either resembles that of the Harney Peak "fine-grained" granite.

BY LEAD-URANIUM RATIOS.

Introduction.

The lead-uranium ratio of each granite was determined from the heavy minerals concentrated by bromoform (G=2.8) from unweathered samples. The magnetic minerals were removed by a small magnet, and the tourmaline of the Harney

---

[11] Popoff, Stephen, Waldbauer, Louis, and McCann, D. C.: Quantitative spectrographic studies of co-precipitation. I. Magnesium in calcium oxalate. Ind. and Eng. Chem. (Anal. ed.), vol. 4, p. 43, 1932.

Peak "fine-grained" granite was removed by electrostatic methods in order to concentrate as much as possible the large free zircons and the small zircons enclosed in the biotite. For both the Game Lodge granite and the Little Elk gneissoid granite the lead-uranium ratio was determined from samples taken from two different exposures. This was not done for the Harney Peak "fine-grained" granite because of the rarity of biotite in which most of the zircon occurs.

To obtain 10 grams of concentrate it was necessary to use approximately 250 grams of Game Lodge granite, 400 grams of Little Elk gneissoid granite, or 200 grams of the Harney Peak "fine-grained" granite which had been gathered for this purpose from outcrops rich in biotite.

The percentage of zircons in the concentrates used is approximately as follows:

Game Lodge granite	1%
Harney Peak "fine-grained" granite	1% to 2%
Little Elk gneissoid granite	1% to 2%.

Methods.

Determination of Lead.

It was necessary to use a procedure by which analyses could be made of very small amounts of lead contained in large samples. The extremely small amount of lead in comparison with the large amounts of other elements present precluded the possibility of micro-chemical analysis. Since small amounts of lead would be lost[12] in the precipitation of SiO_2 and the NH_4OH group, it was necessary to make the complete analysis without a precipitation, and the ordinary methods of analysis of silicate rocks could not be used.

Five to ten grams of the dried concentrates from the bromoform separation were decomposed with H_2F_2 and HNO_3 according to the method used by Hillebrand,[13] dissolved in HNO_3 (approximately 3N), and electrolyzed for 20 to 25 hours at 2 amperes. The PbO_2 was then dissolved from the anode with a hot solution of HNO_3 and alcohol, evaporated to dryness, dissolved in 3N HNO_3, and replated. Replating was usually necessary because a small fraction of the iron from the solution plated out as a red deposit of some form of iron. By replating, this fraction became infinitely small, and a third replating usually eliminated any deposit of iron. The final solution of the PbO_2 from the anode was evaporated to dryness, and the residue dissolved in 1 to 2 cc. HNO_3 and 10 cc. H_2O, and rinsed into a Nessler tube. The solution was neutralized with NH_4OH and saturated with H_2S. Comparisons were then made against standard lead solutions.

---

[12] Hillebrand, W. F., and Lundell, G. E. F.: Applied Inorganic Analysis. John Wiley & Sons. P. 178, 1929.

[13] Ibid., p. 178.

Care had to be taken not to leave the platinum anode in the solution of alcohol and HNO_3 too long, or platinum would be dissolved, making the sulphide solution green in color. If this happened, it was necessary to replate the lead from this solution. Before being used, all reagents were redistilled until spectrographically lead-free. The plating method was tested by plating a known small amount of lead both from synthetic biotite solutions and from HNO_3-water solutions. As small an amount as 0.0000084 g. of lead in 250 cc. of solution plated out within twelve hours.

The sulphide precipitate from the concentrate used for the colorimetric Nessler method was also evaporated, dissolved in 3N HNO_3, and checked quantitatively for lead by spectrographic methods. The determinations arrived at by the colorimetric method and the spectrographic determination of the sulphide were also checked by a third method, namely, spectrographic determination of a solution made by treating the heavy mineral concentrate with H_2F_2 and HNO_3, evaporating it to dryness, and dissolving it in 3N HNO_3. The determinations from all methods agree within experimental error.

Because of the small amount of lead present the atomic weight was not determined. The fact that the results check satisfactorily for the two samples of the Game Lodge granite and that the ratio determined for the Harney Peak "fine-grained" granite checks with that determined by Davis [14 and 15] for the uraninite from the Harney Peak pegmatites seems to indicate that if common lead is present it is very evenly distributed throughout the granites.

Determination of Uranium.

The percentage of uranium in the concentrates was determined by the emanation method using both the fusion and

---

[14] Davis, C. W.: Composition and Age of Uranium Minerals. This Journal, 5th ser., vol. 11, pp. 201-217, 1926.

[15] National Research Council. Committee on the Physics of the Earth. Physics of the Earth—IV. The Age of the Earth. Nat. Research Council Bull. no. 80, pp. 116, 337, 1931.

the H_2SO_4 solution procedures. The solution procedure used by Barker[16] was modified slightly to permit the use of 500 cc. containers instead of test-tubes. The percentage of uranium was calculated by comparison of readings thus obtained with those obtained from analyzed uraninite from the Bob Ingersoll mine, S. D., and analyzed pitchblende from the Great Bear Lake, Canada.

Determination of Thorium.

In the spectrographic analyses made of the H_2F_2-HNO_3 residues by methods already outlined, no thorium was found. The analyses of the Game Lodge granite and the Harney Peak "fine-grained" granite were sufficiently delicate to eliminate any error, greater than the experimental error, which might be due to neglect of the thorium factor in the age calculations. In the case of the Little Elk gneissoid granite, thorium was not found, but a thorough analysis was impossible because of depletion of the sample; therefore, the lead-uranium ratio for this granite may have a greater error than the experimental error of ± 0.02.

Results.

According to the lead-uranium ratios given below all three of the granites are pre-Cambrian. The lead-uranium ratio of the Harney Peak "fine-grained" granite agrees, within experimental error, with the lead-uranium ratio determined by Davis[17 and 18] for the uraninite occurring in the Harney Peak pegmatites. The two determinations of the lead-uranium ratios of samples of the Game Lodge granite also agree within experimental error and indicate that different outcrops of this granite can be correlated by their lead-uranium ratios. The ratios also indicate that the Game Lodge granite is older than the Harney Peak "fine-grained" granite, which fact is in accordance with field data.

The lead-uranium ratios of the two samples of the Little Elk gneissoid granite indicate that this granite is younger than either of the other two granites. The author, however, does not believe the ratios of the Little Elk gneissoid granite to be valid for the following reasons: (1) There is a great variation in the ratios of the two samples, (2) A thorough analysis for thorium was not made, (3) Much of this granite was introduced by lit-par-lit intrusion, possibly accompanied by assimilation of earlier sediments, (4) Microscopic examination of thin sections reveals the presence of small calcite-quartz-muscovite veinlets and the occurrence of noticeable amounts of yellow-brown iron oxides, which facts indicate that the granite has been altered.

---

[16] Barker, Howard H.: (with the collaboration of Herman Schlundt). Experiments on the Extraction and Recovery of Radium. Univ. of Missouri Bull., vol. 24, no. 26, Eng. Exp. Sta., ser. 23, p. 56, 1923.

[17] Davis, C. W.: op. cit., pp. 201-217.

[18] National Research Council, op. cit., pp. 116, 337.

Sample	Percent of Lead	Percent of Uranium	Lead-Uranium Ratio	Average Ratio
Uraninite[19 and 20]			.226	.226
Harney Peak "fine-grained" granite	.00042	.0019	.22	.22 ± 0.02
Game Lodge granite no. A	.00037	.0014	.26	.27 ± 0.02
Game Lodge granite no. B	.00036	.0013	.28	
Little Elk gneissoid granite no. C	.00055	.0037	.15	
Little Elk gneissoid granite no. D	.00041	.0054	.08	

Note—The location of the outcrops from which the samples were taken is given on the map.

CONCLUSIONS.

It seems to the author that the data point strongly to the existence of at least two Black Hills pre-Cambrian granites and possibly a third. The Game Lodge granite is regarded as the older and the Harney Peak "fine-grained" granite the younger. The pegmatites in the Harney Peak area are regarded as later facies of the Harney Peak granite. The possibility that the Little Elk gneissoid granite may be a third granite is recognized but not established. It may correlate with either the Game Lodge granite or the Harney Peak "fine-grained" granite.

The data obtained from the laboratory study of the heavy minerals with the petrographic microscope and the spectrograph indicate that the granites have different characteristics. These two methods probably can be used to correlate or differentiate the granites in different exposures in this area, but they give no indication of the relative ages; and, therefore, exposures of different facies of the same granite, if they vary slightly, may be mistakenly called different granites. The

---

[19] Davis, C. W.: op. cit., pp. 201-217.

[20] National Research Council, op. cit., pp. 116, 337. The ratio reduces to 0.216 when corrected for AcD and common lead.

fact that the lead-uranium ratios of the two exposures of the Game Lodge granite agree within experimental error, and that the ratio for the Harney Peak "fine-grained" granite agrees with that of the uraninite occurring in the associated pegmatites, indicates that the lead-uranium ratio of a granite remains constant. By using this method, then, the possibility of error due to variation in mineralogy and texture in different facies of the same granite is eliminated.

ACKNOWLEDGMENTS.

The author wishes to express his gratitude for the assistance throughout the work of Dr. J. J. Runner and Dr. Louis Waldbauer, of the State University of Iowa. Thanks are likewise due to D. C. McCann, also of the State University of Iowa, for assistance with the analyses of lead and uranium. The author also wishes to acknowledge the kindness of Dr. Hermann Schlundt, of the University of Missouri, and of Dennis Henault of Keystone, S. D., in furnishing samples of pitchblende.

WICHITA,
KANSAS.

FOSSILS FROM THE MARINE PLEISTOCENE TERRACES OF THE SAN PEDRO HILLS, CALIFORNIA.[1]

W. P. WOODRING.

The San Pedro Hills, which reach an altitude of 1,480 feet above sea level, constitute an upland peninsula along part of the southwest side of the Los Angeles Plain (Fig. 1). It has been known since Lawson's reconnaissance of coastal Southern California 40 years ago[2] that an unusually fine set of marine terraces is found in this peninsula, but the fossils so far recorded from them are all from the lowest one.

These terraces and the deposits lying on them were examined during the course of geologic mapping undertaken for the Geological Survey in collaboration with W. S. W. Kew and M. N. Bramlette, though not as much time was devoted to them as they deserve. The report on the geology of this area may be delayed for some time, and it is the purpose of this preliminary account to put on record the discovery of fossils on many of the terraces and to discuss their chronologic and climatic significance. So far, the extensive collections of fossils have been examined only in a preliminary fashion.

In this discussion Pleistocene time is accepted as the period intervening between the advance of the first continental ice sheet in northern United States and the retreat of the last one in the same region. This definition is rather vague, but it is still more vague when applied to coastal Southern California, where the advance and retreat were not directly recorded, and where physical indirect effects of them have not been recognized with any reasonable degree of assurance. In the light of this failure an attempt is made to define Pleistocene time in terms of paleontologic data elsewhere correlated more or less satisfactorily with glacial chronology. Deposits in coastal Southern California that carry horses of the genus *Equus* and elephant-like proboscideans, or beds carrying marine faunas that on a basis of reasonably complete representation have no extinct genera and a low percentage of extinct species—not more than about 5 per cent—are referred to the Pleistocene, whether they are undeformed or deformed. On the basis of this definition, which is admittedly unsatisfactory, the terraces of the San Pedro Hills are Pleistocene, for most of them clearly are later than beds carrying such fossils, and perhaps all of them are. The early terraces may be contemporaneous with the deposition of early Pleistocene sediments, but this matter need not be considered here.

---

[1] Published by permission of the Director of the U. S. Geological Survey.

[2] Lawson, Andrew C.: The post-Pliocene diastrophism of the coast of Southern California: California Univ. Dept. Geol. Bull., vol. 1, pp. 122-128, 1893.

MARINE TERRACES.

Lawson identified 11 terraces in the San Pedro Hills. As a result of the work recently undertaken, 13 main terraces are now tentatively recognized. Five other minor terraces seem to be represented at scattered localities, but their relations are uncertain. The number and correlation of even the main terraces is rather dubious. As may be seen on the 1:24,000 maps of the San Pedro Hills, Torrance, and Wilmington quadrangles, which cover the San Pedro Hills, there are great gaps in the upper and intermediate terraces on the windward side of the hills, where for the most part the terraces are wider and more clearly defined than on the leeward side, and on much of the leeward side they have been destroyed with the exception of isolated remnants. Some of the lower terraces are exceptionally wide on the leeward side in San Pedro and northwest of the town, as there the lower slopes of the hills are made up of soft rocks—diatomite and mudstone—whereas on the upper slopes and on all of the windward side the prevailing rock is cherty, siliceous shale. A further, and virtually insuperable, difficulty in determining the altitude of the base of the sea cliff at the rear of the terraces, and thereby in attempting to trace them across gaps, is presented by the thick cover of débris that was rapidly shed on the emerged platforms by the high cliff that backs platforms on a mountainous coast, such as this one. This feature was clearly described by Professor Davis in his observations on the terraces of the Santa Monica Mountains, the next highland up the coast from the San Pedro Hills.[3] The subaerial platform cover, as Professor Davis called it, is thickest at the rear of a terrace, the very place where the altitude of the plat-

---

[3] Davis, W. M.: Glacial epochs of the Santa Monica Mountains, California: Geol. Soc. America Bull., vol. 44, pp. 1041-1133, pls. 40-56, 26 figs., 1933.

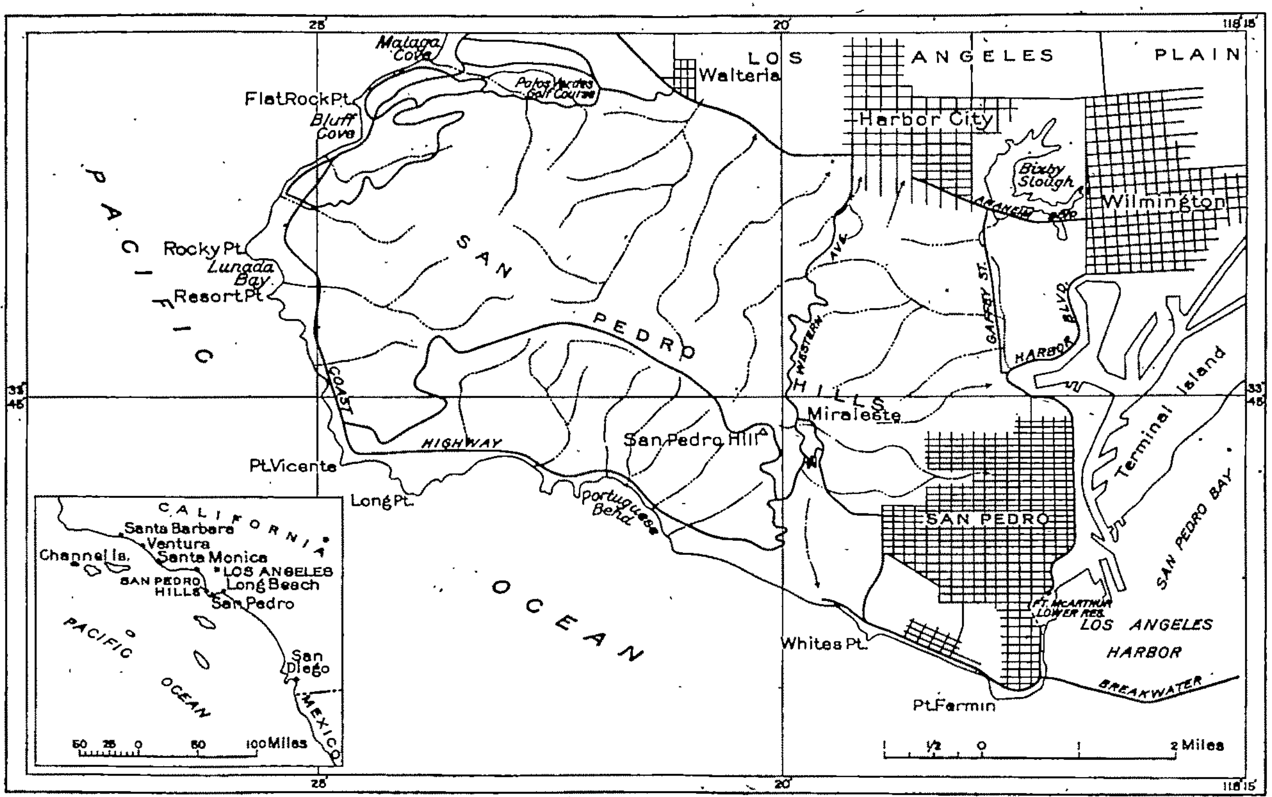


Fig. 1. Outline Map of the San Pedro Hills, California.

Terraces, fossil localities, and faunal facies.

Terrace number	Region where terrace is well-developed	Altitude in feet of change in slope at rear in region where terrace is well-developed	Altitude in feet designated by Lawson (probable equivalents)	Fossil localities	Altitude in feet of fossil localities	Faunal facies
13	South slope of San Pedro Hill	1,325				
12	Southeast slope of San Pedro Hill	1,225	1,240	Highway, southeast slope of San Pedro Hill	1,214	Tide pool
11	South slope of San Pedro Hill	1,150				
10	West slope, inland from Lunada Bay	1,050	1,040			
9	Southeast slope of San Pedro Hill	925	960	Western Ave., southeast slope of San Pedro Hill	925	Tide pool
8	West slope, northwest of Pt. Vicente	850	860			
7	West slope, inland from Lunada Bay	750	700	Western Ave., west of Miraleste School	765	Tide pool
6	West slope, northeast of Lunada Bay	600	550	Del Monte Road, near La Venta Inn	550	Tide pool
				Colinta Road, Miraleste	560	Tide pool
5	West slope, northeast of Lunada Bay	450	400	Coast Highway, northeast of Pt. Vicente	400	Tide pool
4	West coast, east of Flat Rock Pt.	375		Campesina Road, west of Palos Verdes Golf Club	375	Tide pool
				Montemar Road, southeast of Flat Rock Pt.	360	Tide pool
3	West coast, inland from Rocky Pt.	300	300	Bluff Cove	260	Tide pool and protected bay
				Coast Highway, southeast of Resort Pt.	250	Tide pool
				Coast Highway, northwest of Long Pt.	250	Tide pool
				Peck St., San Pedro	240	Tide pool
2	West coast, inland from Rocky Pt.	225	240	Corta Road, Malaga Cove	190	Protected bay and tide pool
				Peck Park, San Pedro	210	Protected bay and tide pool
				South of Standard Tank Farm	220	Protected bay
1	South coast, west of Pt. Fermin	150	160[a]	9 localities on windward side of hills		Tide pool
			120[a]	32 localities on leeward side of hills		Protected bay and tide pool; protected bay and offshore; protected bay; beach

[a] These two terraces, separated by a minor interval, generally less than 40 feet, are grouped as one terrace for the purpose of this account. The lower one is exceptionally wide in San Pedro, but is almost entirely consumed on the windward side. The upper one is the wide lowest terrace on the windward side, but is represented only at scattered localities on the leeward side.

form itself should be determined. On the east side of Portuguese Bend, on the south coast of the hills, the platform cover toward the rear of the first terrace has a thickness of 80 to 110 feet, and the smooth slope inland to the 325-foot level seems to represent a compound cover that conceals one or two terrace profiles. A highway cut east of Point Vicente reveals a continuous cover extending from the third to the first terrace, though the second is consumed along this part of the south coast. At places the altitude of the change in slope at the rear of a terrace differs as much as 50 feet on adjoining spurs, but this difference doubtless is a measure of the difference in thickness of the cover and not a measure of deformation. The covers are thickest on the youngest terraces and probably have been almost entirely, or quite entirely, removed on many remnants of the highest ones. The lack of a concealing cover on the highest ones is offset, however, by their greater destruction. Actual exposures of platforms beneath the covers are generally available only on the present sea cliff, which has retreated as far as the third terrace at only one locality—Bluff Cove—and in fortunately located highway cuts. With few exceptions, they are not exposed on the slopes of arroyos and canyons at any distance from the coast.

On account of these difficulties and their attendant uncertainties, the results of an attempt to trace the terraces around the hills are far from satisfactory. The tentative scheme adopted, the probable relation of the terraces recognized to those designated by Lawson, the fossil localities, and the faunal facies represented are shown in the table on page 295. The altitudes at the rear of the terraces represent the change in slope, which may nearly coincide with the altitude of the platform there, or may be far above it.

FOSSILS.

All the fossil localities on terraces above the first represent highway cuts or other artificial excavations, except the one for the third at Bluff Cove, where the present sea cliff has retreated to it. It is expected that other localities will be found during the course of further residential development in the Palos Verdes Estates and other parts of the hills. The fossil locality on the twelfth terrace at an altitude of 1,214 feet, the highest altitude at which fossils were found, is in a cut on the new highway across the top of the hills, where the following section is exposed:

Section of Deposits on Twelfth Terrace in Highway Cut on Southeast Slope of San Pedro Hill.

		Feet
5.	Reddish brown soil	1-7
4.	Cliff rubble	4-5
3.	Cliff rubble carrying many abalones (*Haliotis cracherodii*) and a few turban shells (*Tegula funebralis*) wedged between stones	2
2.	Coarse sand composed principally of shell fragments and shells; also carries pebbles	1-2
1.	Mixture of cliff rubble, and pebbles and cobbles, many of which are bored	1½-2
	Platform of siliceous shale, surface bored at many places.	

Most of the marine constituents in the beds in this section probably represent material swept up by high waves during violent storms, perhaps during one storm of exceptional violence. They may not have been worked over again by the sea after they were mixed with the rubble that had already begun to accumulate against the cliff backing the platform.

The fossils from the first (lowest) terrace on the windward side of the hills and all from the third to twelfth, with the exception of those from one locality on the third, represent a tide pool facies. This facies, represented at each locality by an average of about 30 species, constitutes an animal community that closely, though not quite exactly, corresponds to the community living in tide pools at the foot of the present sea cliff. It includes rock-clinging shells, some of which live near the upper edge of spray, others between tides, and others on algae-covered rocks in pools that generally are not laid bare; shells and sea urchins that live in rock crevices and holes; shells that live on kelp and eel grass, and among the algae and bryozoa growing on abalones; others that live under stones; and others that burrow in the sand filling rock crevices and holes. A few species, as noted later, are not found in tide pools at this latitude, but in deeper water. The tide pool facies on the first terrace was first discovered and recognized by Mr. and Mrs. E. P. Chace,[4] of San Pedro, at a locality near Point Fermin where chitons are, or rather were, unusually abundant. I am indebted to Mr. Chace for guiding me to this place, which is rapidly disappearing as a fossil locality due to park improvements.

The mixed tide pool and protected bay facies represented on the third terrace at Bluff Cove, on the west coast of the hills, includes most of the abundant tide pool shells and also many others that live in protected bays and inlets, and are abundant on the first terrace on the leeward side of the hills. These protected bay shells are regarded as storm-driven shells swept up from stations to the northeast on the leeward side of the hills. At this locality the fossils are embedded, not in sand or gravel, as they generally are, but in reddish brown fine-grained rubble interpreted as débris that accumulated against the cliff backing the platform.

---

[4] Chace, E. P., and E. M.: An unreported exposure of the San Pedro Pleistocene: Lorquinia, vol. 2, No. 6, pp. 41-43, 1919.

The mixed protected bay and tide pool facies on the second terrace in the Malaga Cove residential district, also on the west coast but closer to the leeward side of the hills, virtually duplicates many collections from the protected bay facies on the first terrace on the leeward side, aside from the greater proportion of tide pool species. At this locality the shells were swept up by waves and trapped in a niche, later sealed by pebbles and cobbles. This is the only place where the sea urchin *Strongylocentrotus* is represented by tests. At two other localities on the second terrace on the leeward side of the hills species of protected bay facies, or of mixed protected bay and tide pool facies, were collected.

The fossils from the first terrace on the leeward side of the hills in the town of San Pedro were first recorded by geologists of the early transcontinental railroad surveys[5] and were described in Arnold's great monograph.[6] The deposits on the first terrace in this region constitute Arnold's upper San Pedro, now known as the Palos Verdes sand.[7] These fossils represent a much greater ecologic range than those from any terrace on the windward side, embracing a mixed protected bay and tide pool facies, a mixed protected bay and offshore facies, a beach facies, and in particular a protected bay and inlet facies containing a considerable admixture of fresh-water snails, and also of isolated bones of land mammals and birds. The protected bay facies yielded most of the 305 species of invertebrates, mainly mollusks, recorded by Arnold. On the leeward side the tide pool facies is best represented near the breakwater, though even here protected bay shells are abundant. The mixed protected bay and offshore facies was found at a locality on the north edge of the Fort McArthur Lower Reservation—Arnold's "Crawfish George's" locality—and at one other place nearby. From this place northward and northwestward around the hills the protected bay and inlet facies is represented. The beach facies was found at only one place in San Pedro. A total of 32 collections was obtained on the leeward side at localities extending from the breakwater northward to Anaheim Boulevard and westward along or near the north edge of the hills to Walteria.

---

[5] Antisell, Thomas: Geological report: U. S. Pacific R.R. Expl., vol. 7, pt. 2, p. 118, 1856. Blake, W. P.: Geological report: U. S. Pacific R.R. Expl., vol. 5, pt. 2, p. 186, 1857.

[6] Arnold, Ralph: The paleontology and stratigraphy of the marine Pliocene and Pleistocene of San Pedro, California: California Acad. Sci. Mem., vol. 3, 420 pp., 37 pls., 1903.

[7] See Woodring, W. P.: San Pedro Hills: Sixteenth Internat. Geol. Cong. Guidebook 15, p. 36, 1932.

CHRONOLOGIC SIGNIFICANCE.

The abundant species in the tide pool facies, regardless of the terrace, are living species, and it is expected that virtually all the rare ones will be found to represent living species. These fossils, therefore, have no value in fixing the age of the terraces other than to indicate that they are Recent or presumably Pleistocene. The mixed tide pool and protected bay facies on the second and third terraces also includes no species that clearly is extinct.

Arnold considered as extinct 28 of the 300 species and varieties of mollusks recorded from the first terrace on the leeward side of the hills, but all except a few have since been eliminated as extinct by the later discovery of living representatives and by changes in identifications. The percentage of extinct species even in this relatively large and reasonably complete fauna probably is not more than two per cent. Some of the extinct species, such as *Turritella jewettii*,[8] may be represented only by detrital material derived from early Pleistocene fossiliferous beds across which the platform of the first terrace in parts of San Pedro and elsewhere was cut, but the recognition of detrital shells in these deposits by any unequivocal criteria is dubious. At all events, the low percentage of extinct species indicates the later part of Pleistocene time. The long series of events that intervened between the deposition of the early Pleistocene beds, which have a considerably greater percentage of extinct species in faunas of comparable size, also points to the later part of Pleistocene time. On the other hand, the considerable history that followed the emergence of the lowest terrace indicates a greater age than very late Pleistocene, as Davis[9] emphasized for the lowest terrace on the coast of the Santa Monica Mountains. A compromise age determination for the first terrace on the basis of these inexact data is late middle or early upper Pleistocene.

---

[8] Though this species was listed by Arnold as extinct (op. cit., p. 46), it generally is regarded as still living (Dall, W. H., U. S. Nat. Mus. Bull. 112, p. 151, 1921; Grant, U. S., IV, and Gale, H. R., San Diego Soc. Nat. Hist. Mem., vol. 1, p. 770, 1931). There are no records of living animals and no authentic records of fresh empty shells.

CLIMATIC SIGNIFICANCE.

The discussion as to climatic significance that follows is based on the assumption that during the time when the terraces were cut the living species found on them as fossils had the same adjustment to their environment that they now have. It should be recognized that this is pure assumption, no matter how reasonable it may appear in view of the close approximation in time.

Nearly all the fossils in the tide pool facies are now living in pools at the base of the present sea cliff on the windward side of the hills. *Acanthina lugubris*, collected at a tide pool locality on the third terrace, is considerably north of its present range, the northern limit of which is San Diego. On the contrary, a few species (*Acmaea mitra*, *Tegula brunnea*, *Crepidula excavata*, *Bittium armillatum*, *Bittium eschrichtii montereyense*) that are not found in tide pools in the latitude of San Pedro, but live at a greater depth offshore, have been recognized in the tide pool facies, and others probably will fall in the same class when the collections are fully identified. The specimens representing these species are regarded as storm-swept shells carried in from the offshore part of the platform. Evidence pointing to storm waves as a transporting agent at several localities has already been presented. Further evidence is afforded by the finding at the rear of the first terrace near Point Fermin of several specimens of small tide pool species in fine-grained cliff rubble lying on an artificially exposed face of the ancient sea cliff that has a slope of 60°. The altitude of the platform at the base of the cliff here could not be determined, but the shells clearly are at a considerable distance above it. This admixture of storm-carried shells probably accounts for the more northern aspect of the chitons at the locality on the first terrace near Point Fermin discovered by Mr. and Mrs. Chace, on the basis of which the conclusion was drawn that the temperature of the water when the fossils lived was a little lower than it now is.[10]

---

[9] Davis, W. M.: op. cit., pp. 1072-1073.

The mixed tide pool and protected bay facies on the third and second terraces embrace species that are within their present range, with the exception of the following, all of which are southern or of southern aspect:

Species of Southern Aspect in Mixed Tide Pool and Protected Bay Facies on Third and Second Terraces.

Terrace	Species	Present range[a]
3	Gouldia branneri (Arnold)	"San Diego to Panama"[b]
	Fragum biangulatum (Broderip and Sowerby)[c]	Catalina Island to Colombia
2	Acanthina lugubris Sowerby[c]	San Diego to Magdalena Bay, Lower Calif.
	Pecten vogdesi Arnold	Generally considered identical with Gulf of California species known as *P. cataractes* Dall
	Gouldia aff. varians (Carpenter)[c]	Perhaps identical with *G. varians*, which ranges from Gulf of California to "Panama"

[a] Present range in this table and succeeding one taken from Dall (op. cit.), and Grant and Gale (op. cit.).

[b] A small living race of this species is represented in collections from Scammon Lagoon, Lower California, at the Academy of Natural Sciences of Philadelphia and in collections from Magdalena Bay and nearby localities at the U. S. National Museum. A few bleached larger shells in the collections of the U. S. National Museum, dredged in shallow water at San Diego, may represent fossils eroded from Pleistocene beds bordering San Diego Bay, where *branneri* is known to occur.

[c] Not heretofore recorded as a fossil in this region.

Conflicting claims have been made for the climatic significance of the fossils on the first terrace on the leeward side of the hills. Arnold[11] observed that some species are not found in shallow coastal waters as far south as San Pedro, but that more are confined to regions south of San Pedro, and reached the conclusion that during the time when the deposits on this terrace were laid down the climate was warmer than it now is. This conclusion was further emphasized by J. P.

---

[10] Berry, S. Stillman: Fossil chitons of western North America: California Acad. Sci. Proc., 4th ser., vol. 11, pp. 408-409, 417-418, 1922.

[11] Arnold, Ralph: op. cit., pp. 66-67, 1903.

Smith,[12] who estimated that the temperature was about 4° F. above the present temperature, and by H. R. Gale,[13] who placed these deposits in the last interglacial period. At a date preceding Arnold's work, however, one worker came to the conclusion that the fossils at one locality—Arnold's "Crawfish George's" locality, already mentioned—represent a period when the temperature was lower than it now is.[14] The species of northern and southern aspect in the deposits on the first terrace on the leeward side of the hills are as follows:

Species of Northern and Southern Aspect in Deposits on First Terrace on Leeward Side of Hills.

Northern species	Present range
Fusitriton oregonensis (Redfield)	Bering Sea to San Diego in deeper water
Boreotrophon pacificus (Dall)[a]	Arctic Ocean to Acapulco, Mexico, in deeper water
Boreotrophon cf. multicostatus (Eschscholtz)	Bering Sea to San Pedro (*B. multicostatus*)
Amphissa columbiana Dall	Alaska to San Pedro
Neptunea tabulata (Baird)[b]	British Columbia to San Diego in deeper water
Exilioidea rectrirostris (Carpenter)	Alaska to Cape San Quintin, Lower California
Acila castrensis (Hinds)[b]	Bering Sea to San Diego
"Pecten" caurinus Gould[a]	Alaska to Siletz Bay, Oregon
Cerastoderma nuttallii (Conrad)	Bering Sea to San Diego; Lower California?

Southern species	Present range
Purpura monoceros (Sowerby)[a]	Lower California
Centrifuga leeana (Dall)[a]	Guadalupe Island to Cedros Island, Lower California
Eupleura muriciformis (Broderip)[a]	Gulf of California to Colombia
Macron aethiops kellettii (Adams)	Catalina Island?; Lower California and Gulf of California
Anadara perlabiata (Grant and Gale)	San Diego?; Lower California to Panama
Pecten vogdesi Arnold[a]	Generally considered identical with Gulf of California species known as *P. cataractes* Dall

---

[12] Smith, J. P.: Climatic relations of the Tertiary and Quarternary faunas of the California region: Calif. Acad. Sci. Proc., 4th ser., vol. 9, p. 137, 1919.

[13] Gale, H. R.: in Grant, U. S., IV, and Gale, H. R., San Diego Soc. Nat. Hist. Mem., vol. 1, p. 73, 1931.

[14] Ashley, G. H.: The Neocene stratigraphy of the Santa Cruz Mountains of California: California Acad. Sci. Proc., 2d ser., vol. 5, pp. 339-346, 1895.

Gouldia branneri (Arnold)[c]	"San Diego to Panama"
Gouldia aff. varians (Carpenter)[d]	Perhaps identical with *G. varians*, which ranges from Gulf of California to "Panama"
Taras sericatus (Reeve)	San Diego to Panama
Laevicardium elatum (Sowerby)	San Pedro to Panama
Trachycardium procerum (Sowerby)	Scammon Lagoon, Lower California to Peru
Fragum biangulatum (Broderip and Sowerby)[d]	Catalina Island to Colombia
Chione gnidia (Broderip and Sowerby)	Cedros Island, Lower California to Peru
Dosinia ponderosa (Gray)[d]	San Diego to Peru
Tellina rubescens Hanley[a]	Scammon Lagoon, Lower California to Peru
Mulinia modesta Dall[a]	Lower California and Gulf of California

---

[a] Based on Arnold's record.

[b] Based on Ashley's record. It is not clear whether all the fossils listed by Ashley are from the "point where a short drain has cut into the cliff" (Arnold's "Crawfish George's" locality).

[c] See note c, p. 301.

[d] Not heretofore recorded as a fossil in this region.

It will be observed that only one of the northern species—"*Pecten*" *caurinus*—is actually outside its present range, whereas all except two or three of the southern ones are, some as much as 400 miles.

The southern species point to warmer coastal water than at the present time. The simplest explanation for the northward extension of their range is the one that has been proposed; that it took place during an interglacial period when the temperature of coastal waters was higher than it is now. This view ignores, however, the species of northern aspect. Most of these northern species are known only from Arnold's "Crawfish George's" locality. This is the only place where I collected *Fusitriton oregonensis*, *Amphissa columbiana*, and *Exilioidea rectirostris*, as well as the only one at which foraminifera were found. *Boreotrophon* cf. *multicostatus* was collected here and at one other locality farther south. Moreover, none of the southern species was found in this region. If the apparent climatic implication of the fossils is to be translated into terms of glacial-interglacial chronology, the fossils in this region are glacial, as Ashley's claim implies. As it is manifestly incongruous to attribute deposits on the same terrace to interglacial and glacial periods at different localities, it is evident that the fossils have some other significance. The northern species are confined to the part of the leeward side of the hills that faced the open ocean when the terraces were formed. None was found at the northeast end and on the north side of the hills, which faced a shallow bay, where the southern species are most abundant. This distribution strongly suggests that the specimens representing the northern shells are storm-driven shells, though storms of exceptional severity would be required to move them from the depth at which they now live in this latitude. This view fails to account, however, for *"Pecten" caurinus,* which is entirely outside its present range. The absence of any of these northern species at tide pool localities on the windward side, where storm waves were most powerful, probably is to be attributed to the steeper offshore slope there. Some of the northern shells, notably *"Pecten" caurinus,* recorded only by Arnold, may represent detrital material derived from the early Pleistocene beds, but again no satisfactory criteria for recognizing such material are apparent.

The southern species are not open to the same suspicion. Their presence so far north implies warmer coastal waters at this latitude. The distribution of terrace fossils of different climatic facies along the coast of Southern California throws some doubt, however, on the ready translation of the climatic implication of the southern species into terms of glacial-interglacial chronology. Southern species are found as fossils on the lowest terrace from San Diego northward to Santa Monica. They are absent farther north in Southern California and it has been suggested that fossils from the lowest terrace near Santa Barbara indicate a glacial period.[15] If southern species continue to be found as terrace fossils from San Diego to Santa Monica, particularly if they are found on more than one terrace in successive series, as in the San Pedro Hills, and if collecting continues to reveal only terrace fossils of glacial aspect, again particularly on more than one terrace, northward from Ventura, still further doubt will be thrown on the glacial-interglacial value of the southern species, as it is altogether improbable that the terraces south of Santa Monica are interglacial, whereas those in Southern California northward from Ventura are glacial. The geographic framework of the coast may have some bearing on the distribution of the southern species. During a still undated part of Pleistocene time, doubtless during at least part of the time when the terraces of the San Pedro Hills were being formed, the Channel Islands, which lie northwest of the hills, were joined to the present seaward end of the Santa Monica Mountains, forming a peninsula that extended far out into the ocean. Evidence for this seaward extension of the Santa Monica Mountains is afforded by the Pleistocene elephants found in terrace deposits on two of the islands—Santa Rosa[16] and Santa Cruz.[17] This peninsula protected the area to the south, in which the San Pedro Hills lie, from southward-drifting cold coastal water, a matter that was considered by H. R. Gale[18] and by Davis.[19] The northern limit of the southern species coincides with the base of the peninsula, but it is not known whether the relation is a causal one.

---

[15] Grant, U. S., and Strong, A. M.: Fossil mollusks from the vertebrate-bearing asphalt deposits at Carpenteria, California: Southern California Acad. Sci. Bull., vol. 33, pp. 7-11, 1934. Fossils of similar climatic implication from the lowest terrace west of Santa Barbara are recorded by Oldroyd and Grant. Nautilus, vol. 44, pp. 91-94, 1931.

If the lowest terrace in the San Pedro Hills is interglacial, it follows that the second and third also are, as they carry southern species and, so far as now known, are free of the embarrassment of northern species. The tide pool fossils on terraces above the third have no climatic implication. If new localities are found on these terraces on the leeward side of the hills they may reveal protected bay species that have some climatic implication. A discrete assignment of all the terraces to the recognized interglacial periods with appropriate uplifts needs strong supporting evidence to be convincing.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.

---

[16] Stock, Chester, and Furlong, E. L.: The Pleistocene elephants of Santa Rosa Island, California: Science, vol. 68, pp. 140-141, 1928.

[17] Chaney, R. W., and Mason, H. L.: A Pleistocene flora from Santa Cruz Island, California: Carnegie Inst., Washington, Pub. 415, p. 20, 1930.

[18] Gale, H. R.: op. cit., pp. 39, 64.

[19] Davis, W. M.: op. cit., p. 1110.

SCIENTIFIC INTELLIGENCE.

CHEMISTRY.

The Fundamentals of Chemical Thermodynamics. Part I. *Elementary Theory and Applications*; Part II. *Thermodynamic Functions and Their Applications*; by J. A. V. BUTLER, Lecturer in Chemistry in the University of Edinburgh. Part I: 1928. Pp. xi, 207; 51 figs.; price, $2.00. Part II: 1934. Pp. x, 271; 43 figs.; price $3.00. The Macmillan Company, London and New York (60 Fifth Avenue). Part I of this work appeared about six years ago and it was given due notice in journals of that time. It comprises the material used by the author in a first course in thermodynamics. It intentionally avoids the general use of thermodynamic functions, especially the entropy, and the results are obtained mainly by employing cyclic processes. Part II, to quote the author, "is tolerably complete in itself." It is the opinion of the reviewer that a student with an understanding of elementary physical chemistry could begin with this second volume in which the subject is developed from the functional point of view. The treatment is modern, and, owing to the small size of the volume, is almost too concise. It might be called a "road map" to thermodynamics. It is surprising to find in both volumes that a condition of equilibrium is simply that $(\Delta A)_T \geqq 0$. BLAIR SAXTON.

GEOLOGY.

The Changing World of the Ice Age; by REGINALD ALDWORTH DALY. Pp. xix, 271; 149 illus. and 29 tables. New Haven, 1934 (Yale University Press, $5.00).—For the Silliman Lectures delivered at Yale University early in 1934, lectures whose text is published with some additions in the present volume, Professor Daly has selected an impressive theme: the far-reaching secular effects of the Pleistocene glaciers, especially the great ice sheets of the northern hemisphere. His discussion is not, however, a mere record of Pleistocene conditions and events, valuable as such a record is in itself. Its ultimate objective is an inquiry into the physics of the Earth's body, by the use of data on the reactions of the Earth's crust to the loads of ice and the changes of sea level that gave special character to the Pleistocene epoch. This objective lends point and personality to the discussion, lifting it far above the level of the encyclopedic reference work, despite the fact that the book contains an extraordinary bulk of well-documented information. Not only is the volume a major contribution to geology, but unlike many other great contributions it is so written as to be virtually as comprehensible to the scientifically minded layman as to the professional geologist; witness its selection by the Scientific Book Club. Remarkably few technical terms are used, and nearly all the terms used are clearly explained.

No reader can fail to be impressed with the care with which the theme has been developed into a masterly piece of exposition. The general trend of the argument is inductive, reasoning from the glacial evidence to the inferred effects on the crust, although at many points, as for example the discussion of emerged strandlines, extensive deductive reasoning is employed.

Beginning with the ice sheets, we are given data on their probable extent, volume, and contemporaneous existence, and effect on sea level. We then read summary accounts of the waning of the latest Fennoscandian and Labrador-Keewatin ice sheets, and the record of the seas and lakes associated with them. Here the postglacial updoming of the glaciated tracts is specially emphasized. In the chapter on the Earth's Deformation and Recoil, a geophysical and structural discussion, we have the core of the book, an attempt at quantitative evaluation of plastic and elastic elements in the uplift of the crust following relief of ice load. In discussing plastic deformation, the author abandons the bulge hypothesis, involving horizontal subcrustal flow at slight depth, in favor of a *punching hypothesis*, outlined below. The former concept, requiring a viscous bulge, or wave progressing inward from the periphery of a region relieved of ice load, is held invalid chiefly on the ground that such a bulge is nowhere recorded by drainage patterns or by the older late-Glacial beaches. The punching hypothesis (p. 122) assumes that the subcrustal outward flow resulting from ice loads on the crust takes place below the 1000-kilometer level. A prolonged heavy ice load causes both plastic and elastic basining of the underlying crust, accompanied by slight uplift ("super-elevation") of the surrounding region. With deglaciation, there is immediate elastic uplift, extending well beyond the glaciated region, followed by slow plastic up-punching within a "hinge zone," an assumed belt of vertical fractures encircling the glaciated region. The fracturing then permits "snapping down" of the superelevated periglacial belt to its preglacial position. Displacement along each fracture is considered so slight as to be inconspicuous at the surface.

Although this hypothesis is ingenious, and meets the stated facts more satisfactorily than the bulge concept, it is not demonstrated by the evidence now available. Further progress in this direction will have to await the accumulation of more facts, but in the meantime speculations such as the one offered by Daly are valuable in that they stimulate thought and provoke discussion.

The chapter on High Sealevels of the Pleistocene presents a splendid deductive argument (pp. 152-157) showing why Pleistocene strandlines can not be uniformly high above present sea level. Uniformity has been assumed by some students of this problem, and the argument here set forth should do much to discourage hasty correlations and to make investigators keenly alive to the complexity of this problem. The same chapter tentatively ascribes worldwide strandlines a few meters above present sea level, earlier held by the author to date from the climatic optimum, accompanied by decreased land ice, of several thousand years ago, to delayed plastic adjustment of the Earth to the weight of water piled on the sea floors by the wasting of the last Pleistocene ice sheets. The suggestion is speculative but suggestive, and emphasizes the fact that some students of Pleistocene strandlines have stressed the climatic factor while giving insufficient attention to structural or tectonic factors.

Probably no geologist, confronted with the task of preparing such a study as this, would consider his work complete without attempting at this point to discuss the bewildering array of correlations, coastwide, continentwide, and even worldwide, of elevated Pleistocene and Recent strandlines. Daly's brief but discriminating exposition of the correlations of Dépéret, Dubois, Passemard, Antevs, Cooke, and Suter leaves one very strongly impressed with the need for more reliable and unprejudiced facts before any sound correlation can be attempted.

Directly connected with problems of submerged and emerged strandlines is the now venerable coral reef problem. It is appropriate therefore that Daly, author of one of the two chief hypotheses of reef origin, should take this opportunity to restate, with some modification, the case for the Glacial Control theory. The argument stresses heavily the evidence for flatness and uniformly shallow depth of lagoon floors (p. 228), the strongest evidence for this theory. It clears up a point of confusion by restating (p. 247) the view that the sub-reef platforms were wave-cut in *preglacial* time, and that the attempt of W. M. Davis to refute the theory was based in part on the misunderstanding that the cutting of the platforms was accomplished chiefly during the Pleistocene. No specific answer is made to Davis' argument that platform abrasion must have been accompanied by the development of wave-cut cliffs, which nevertheless are rare; one infers that Daly regards the cliffs as having been destroyed by subaerial erosion during the Pleistocene. This point has been advanced so clearly by Davis that it deserves a definite answer. In any case the current rival theories are brought measurably nearer agreement by Daly's ready acceptance of local subsidence, together with Davis' admission of restricted glacial control.

Returning to the book as a whole, we may say that no argument that rests in large part on facts not yet clearly proved and on extensive deductive reasoning, can hope to escape criticism. The assumed basining of Greenland (pp. 11, 51) under ice weight, for example, rests upon a few sonic measurements of ice thickness made by Wegener, and the interior lowland apparently shown by Wegener's measurements might equally well be considered erosional, until more evidence is available. Again, the correlation

(p. 34) of Penck and Brückner's four stages of glaciation in the Alps with the four principal stages in northeastern North America is not supported by any facts known to the writer. Some authorities are not yet willing to call such correlation even a strong probability. Again, the evidence for a Late-Glacial superelevated belt of land (p. 109) off the present Atlantic Coast of North America between New Jersey and Newfoundland is very tenuous indeed. There is little value, however, in enumerating such points. Each reader will make his own collection of them, and the collections will vary with the point of view (and perhaps the prejudices) of the reader. But taken all together, they can not detract seriously from the essentially great contribution made by this book, marshaling as it does an extensive array of facts from very widely scattered sources, weaving them into a connected account, and offering, as a result, a number of hypotheses which although speculative, advance us appreciably nearer a sound understanding of the Earth's reaction to changing loads. Some of the speculations will be modified; others may be rejected entirely in the light of new data, but in its essence the work justifies to the fullest extent that much-abused adjective, *scholarly*, and may fairly be termed a milepost in the investigation of the Earth's crust. RICHARD FOSTER FLINT.

Useful Aspects of Geology: An Introduction to Geological Science for Engineers, Mining Men, Prospectors, and all interested in the Mineral Industries; 2d Edition; by S. J. SHAND. Pp. x, 183; 30 figs. London, 1934 (Thomas Murby & Co., 6s. net).—The first edition of this excellent booklet appeared in 1925, and now that a new edition was demanded, a somewhat revised and amplified version has been printed. The author confesses that the sedimentary mineral deposits had been rather shabbily treated in the first edition, and to rectify this, they are now given a chapter to themselves. Despite this addition, the book has by the use of smaller type been slightly reduced in size. A. K.

MISCELLANEOUS SCIENTIFIC INTELLIGENCE.

The Great Design: Order and Intelligence in Nature. Edited by FRANCES MASON, with an introduction by SIR J. ARTHUR THOMSON. Pp. 324. New York, 1934 (Macmillan Company, $2.50).—Mrs. Mason's purpose in forming this collection of fourteen essays is a religious one: to show that there is a Living Intelligence behind Nature, that "science is discovering for religion a sublimer universe and thus supplying a surer ground for Faith." Sir J. Arthur Thomson explains the purpose thus in his Introduction: "What Science seems to show is that we cannot 'make sense' of the Universe and our place in it unless we believe in the reality of Purpose—of Divine Design .... Is the scientifically disclosed world of order and intelligence one in which the religious mind can breathe freely?" Five of the contributors write with conviction to expound the belief in "the Creative and Directive Power of God"; five contributors indicate briefly that perhaps they sympathize with this faith; four have nothing to say about belief. Sir Arthur and other contributors state clearly that the interpretation of the universe as a revelation of "the Power and Wisdom of God" is not scientific, that science can go no further than "verifiable empirical factors." They distinguish between how the world seems to them as scientists, and how it seems to them "as men." They are concerned with "what the plain man intuitively feels." Eleven of the essays are excellent summaries of phases of science, zestfully and entertainingly written by competent men.

HENSHAW WARD.

General Astronomy; by H. SPENCER JONES. 2d Edition. Pp. viii, 437; 27 pls. and frontispiece. New York, 1934 (Longmans, Green & Co., $3.75, and Edward Arnold & Co., London).—The first edition of this book appeared in 1922; so great has been the progress of the science in the intervening twelve years that much of this earlier volume has had to be rewritten. The second edition is for the moment perhaps the most complete account of the subject in English, and it is characterized by good judgment and a fine conservatism in dealing with conclusions that have not yet been thoroughly confirmed. When the first edition was going through the press the author was on his way to South Africa to take charge of the Observatory at Capetown, and as a result a number of obvious slips were allowed to pass the proof readers. The reviewer believes that all but three or four of these have been corrected in the second edition. The eclipse map on page 186 perpetuates a mistake made in the United States Nautical Almanac Office and does not show the correct relation between West Africa and the path of totality. In the mass-luminosity diagram on page 342 all the magnitudes should be multiplied by ten. The author is unusually careful in historical reference, but Hertzsprung's name does not appear often enough, and Kohlschütter's does not appear at all. Matters of this sort, however, (and some of them may be merely differences of opinion) are bound to occur in dealing with so vast an accumulation of new material.

FRANK SCHLESINGER.

Report of the Science Advisory Board of July 31, 1933, and *May 28, 1934*. Pp. 303. Washington, September 20, 1934.—The National Research Council was established at the request of President Wilson in 1916 and perpetuated by his order of May 11, 1918. The Science Advisory Board, acting through the National Academy of Sciences and National Research Council, followed on

July 31, 1933, through the action of President Roosevelt. He also. on July 31, 1933, appointed nine men prominent in science, as members of the Science Advisory Board for two years. To these he added six others on May 28, 1934. Dr. Karl T. Compton of the Massachusetts Institute of Technology is the Chairman of the Board, and Dr. R. A. Millikan, Isaiah Bowman and Charles D. Reed constitute the initial Committee.

The activities of the Board embrace the following lines of work: *A*. Agriculture, including the Weather Bureau, Genetics, etc.—*B*. Bureau of the Budget. *C*. Commerce. *D*. Department of the Interior: (Geological Survey, Bureau of Mines, etc.) *E*. Joint Agencies: (Land-use problems; Mineral policy). *F*. Navy Department. *G*. War Department. *H*. Special Bureaus and Agencies: (Railway research, etc.). *I*. Other Activities: (Dues to International Unions; Recovery program of science progress, etc.). The Appendices include a series of Reports: as, Weather Bureau, Bureau of Standards, Industrial Research, etc. Of special interest is the proposal of a recovery program of Science progress.

This brief summary of the contents of so important a volume suggests many ways in which the science of the country and its value to the public may be wisely developed.

OBITUARIES.

DR. ROBERT C. BURDETTE, associate entomologist of the New Jersey Agricultural Experiment Station, Rutgers University, died on January 6 at the age of thirty-six.

DR. BERTRAM H. BUXTON, the English bacteriologist and biologist, died on December 5, 1934, at the age of eighty-two.

DR. CORNELIA MARIA CLAPP, from 1873 to 1916 professor of zoology at Mount Holyoke College, died on January 1 at the age of eighty-five.

DR. HERDMAN FITZGERALD CLELAND, professor of geology at Williams College, died on January 24 at the age of sixty-five.

DR. ROLAND BURRAGE DIXON, professor of anthropology at Harvard University since 1916, died on December 20 at the age of fifty-nine.

SIR JAMES ALFRED EWING, in 1873 professor of mechanical engineering at the University of Tokyo, and in 1890 professor at the University of Cambridge, died recently at the age of eighty. In 1916, he was made principal and vice-chancellor of the University of Edinburgh.

DR. WILBUR GARLAND FOYE, professor of geology at Wesleyan University since 1924, died on January 8 at the age of forty-nine.

DR. CHIYOMATSU ISHIKAWA, honorary professor of zoology at the Tokyo Imperial University, died on January 17 at the age of seventy-four.

Dr. Albert Mann, a worker in the field of diatomy, died on February 1 at the age of eighty-one. He was a professor of botany in the Ohio Wesleyan University, 1894 to 1900; of George Washington University, 1907-1909; and with the Carnegie Institution since 1919.

Dr. Theobald Smith, prominent in his work on animal pathology, died on December 11 at the age of seventy-six. He was professor of bacteriology at the George Washington University from 1886 to 1895 and of comparative pathology at Harvard from 1896 to 1915. He was also director of the department of animal pathology in the Rockefeller Institute of Medical Research from 1915 to 1929.

PUBLICATIONS RECENTLY RECEIVED.

Um das Geologische Weltbild; Malleo et Mente; Erich Haarmann. Stuttgart W, 1935 (Ferdinand Enke, RM. 5.80).

Useful Aspects of Geology; by S. J. Shand. Second edition. London, 1934 (Thos. Murby & Co., 6/-).

Electrons (+ and —), Protons, Photons, Neutrons, and Cosmic Rays; Robert A. Millikan. Chicago, 1935 (University of Chicago Press, $3.50).

Blue Hill Meteorological Observatory of Harvard University. No. 2. Subsidence within the Atmosphere; by Jerome Namias.

Aristotle, Galileo, and the Tower of Pisa; by Lane Cooper. Ithaca, N. Y., 1935 (Cornell University Press, $1.50).

Geological Society of America. Memoir 2. Paleozoic Plankton of North America; by Rudolf Ruedemann. 1934.

X-rays in Theory and Experiment; by Arthur H. Compton and Samuel K. Allison. Second Edition. New York, 1935 (D. Van Nostrand Co., $7.50).

Chemical Kinetics and Chain Reactions; by N. Semenoff. Oxford and New York, 1935 (Oxford University Press, $10.50).

The Museum of Comparative Zoology, Cambridge, Mass. Memoir 52. Geology of Cape Cod; by Woodworth and Wigglesworth.

Logik der Forschung; zur Erkenntnistheorie der Modernen Naturwissenschaft von Karl Popper. Pp. 248. Vienna, 1935 (Julius Springer, RM. 13.50).

Biology for Everyman; by Sir J. Arthur Thomson. Vols. I and II. New York, 1935 (E. P. Dutton & Co., 2 vols. complete $5.00).

Nitrogen Systems of Compounds; by E. C. Franklin. New York, 1935 (Reinhold Publishing Corp., $7.50).

Clinical and Pathological Applications of Spectrum Analysis; by Walther Gerlach and Werner Gerlach, translated by Joyce Hilger Twyman. London, 1935 (Adam Hilger, 14s. 6d. net).

Principles of Genetics and Eugenics; Nathan Fasten. Boston, 1935 (Ginn & Co., $2.80).

AMERICAN JOURNAL OF SCIENCE

APRIL 1935

Sec. No.........
Book No.........
LIBRARY

STREAM CARVED SLOPES AND PLAINS IN DESERT MOUNTAINS.

ROSS FIELD.[1]

While making a detailed survey of a locality in the Humboldt Mountains of Nevada, the writer became interested in the formation of plains by streams under arid conditions. Later he made an extensive trip to southeastern California and southwestern Arizona in company with Mr. Eliot Blackwelder, devoting special attention to the study and measurement of such features. Later an examination was made of the views of other students of the subject with the hope of harmonizing some of the apparent conflicts of opinion. This paper is written for the purpose of supplementing and clarifying some of the interpretations now current in geologic literature regarding desert features.

SUMMARY OF THE LITERATURE ON DESERT PLAINS.

It seems unnecessary in this essay to recount in detail the observations and opinions already published by geomorphologists on the subject of desert plains. Any one interested in the historical development of such ideas up to this time will do well to consult the recent papers by Davis (4, 5, 6), Blackwelder (2), and especially Johnson (8, 9, 10). By way of introduction, however, there is offered here a brief summary of the contributions that have been made by earlier writers. The first clear statement appears to be that of G. K. Gilbert (7, pp. 128-132) who in 1875 described the sloping rock plains around the Henry Mountains in Utah and concluded that they were due to lateral erosion by the graded streams descending from the mountains. Ogilvie (14) later reached a similar but less clearly stated conclusion regarding the isolated Ortiz

---

[1] This paper is essentially a condensation of an unpublished dissertation in the library of Stanford University. During the absence of the author in Bolivia, it has been condensed, edited, and arranged for publication by Eliot Blackwelder.

AM. JOUR. SC.—FIFTH SERIES, VOL. XXIX, NO. 172, APRIL, 1935.

Mountains in New Mexico. The term ***conoplain*** which she applied to such features has been ignored by later writers.

McGee (13) and Keyes (11) added facts of observation but their interpretations of the origin of the plains have proved unsatisfactory to nearly all recent students of the subject.

Among later writers Paige (15) was the first to analyze clearly the formation of plains underlain by rock but veneered with alluvium under conditions prevailing in an undrained desert basin. His report was soon followed by a more elaborate paper by Lawson (12) starting with the same assumptions and carrying the cycle of erosion deductively through to the ultimate stage. He pointed out that the continually rising deposit of alluvium in the basin would necessitate the formation of a rock slope which would generally be convex upward along the axes of stream flow and to which he applied the name ***suballuvial bench.*** In the final stage of erosion the mountain mass is reduced to a broad dome of rock swathed in alluvial deposits. Such features he called ***panfans.***

Bryan (3), after studying critically a typical part of Arizona adjacent to McGee's district, emphasized the great extent of the rock plains made by stream erosion and employed McGee's word "pediment" as a technical name for them. This term has since found general acceptance. He differed from Gilbert and his followers in ascribing much less value to side-cutting by desert streams and much more to the work of rills or unconcentrated runoff which he designated as the "agencies of slope retreat." He discussed the gradients of pediments and mountain slopes, and argued that they were conditioned by such factors as climate and the texture of the colluvial débris.

Later Davis (5, 6) entered the discussion of the papers by Lawson and Bryan, apparently agreeing largely with both of them rather than with the Gilbertian group, as regards the relative importance of side-cutting by streams and slope gradation by sheet wash and rills.

Berkey and Morris (1, pp. 330-332), reflecting the then unpublished views of Johnson, described similar rock plains in the Mongolian desert and explained them as being due to corrasion by graded streams.

Blackwelder (2) discussed the contrast between rock slopes (pediments) cut by streams deflected sidewards while at grade and the depositional slopes (fans and bajadas) built by streams because they were below grade. He emphasized the fact that the latter are relatively abnormal, whereas the former increase in extent steadily until in old age they dominate the desert landscape. He also discussed certain complications due to climatic changes.

Johnson (10) later gave a clear exposition of the problem, essentially agreeing with Gilbert (7) and others in emphasizing the dominant importance of lateral corrasion by streams. He discussed in detail and with acumen the continuous regrading of pediment surfaces as the cycle of erosion proceeds toward old age. With Lawson (12) he took issue on the grading of pediments but he seems to confuse the latter with Lawson's suballuvial bench. As will be shown later, these two features are probably distinct. Johnson (9) also argued deductively that the cross section of each V-shaped element of a pediment must necessarily be convex like an alluvial fan and he cited localities in southern Arizona and New Zealand where he found confirmation of the idea. Blackwelder and the writer of this paper were not successful in finding convex fan-shaped reëntrants along the margins of the numerous pediments in the lower part of the Colorado River valley, where conditions are favorable for their study. The problem is complicated by the fact that there have been important climatic changes which have induced an alternation of deposition and intrenchment while the pediments were being formed. It therefore seems probable that the question can be cleared up only by very detailed instrumental surveys in localities which are exceptionally favorable.

ANALYSIS OF THE FORMATION OF DESERT PLAINS BY STREAM EROSION.

It is an elementary principle that the immediate goal of stream action is a smooth channel whose profile is concave upward. The gradient of this profile is greatest at the head of the stream and flattest near the mouth. Assume an upfaulted land mass with the sea against the fault scarp, as in Figure 1. The first streams that notch the cliff will soon develop profiles concave upward and with short radii of curvature. As their valleys are extended inland and their lower ends maintained at the same elevation (sea level) they must develop profiles in which the radii of curvature are steadily increased at every point in the profile, the amount of increase being progressively greater upstream.

Assume now that the uplifted block is situated in a desert region and that there is a closed basin in place of the sea. The same relations will hold except that after the streams reach the center of the basin, instead of having the lower ends of their profiles fixed, the lower ends will be raised vertically as the basin fills with alluvium. Besides being raised vertically, at any one point the stream profiles will have their radii of curvature continually increased. The relations that will normally develop are shown in Figure 2.

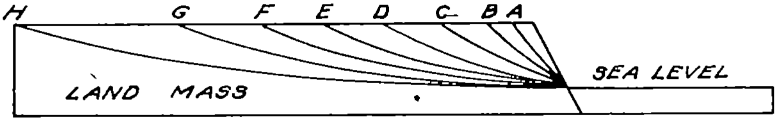


Figure 1. Successive stream profiles on a fault block lifted above sea level.

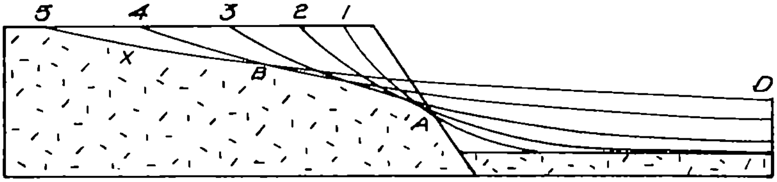


Figure 2. Successive stream profiles upon an elevated fault block adjacent to an undrained desert basin. A-B is the suballuvial bench, B-D the alluvial fan, and B-X the pediment.

In the diagram it will be noted that the successive layers added to the detrital deposits in the basin are not essentially uniform in thickness as postulated by Lawson (12, page 35) but are wedge-shaped with the thinnest part of the wedge upstream. This is due to the fact that the angle of grade of the streams for each successive stage in the process is less and therefore the profiles converge upstream.

As will be shown later, the larger streams issuing from the mountain mass, with their tributaries, are believed to be the principal agents in sculpturing the upland. Lawson draws his diagram through a spur of the mountain front and does not indicate what the conditions are along the major streams. Johnson draws his diagram along the major streams for a distance and then turns abruptly up a mountain slope. The writer's diagram (Figure 2) shows the profile along a major stream course.

The factors controlling the retreat of the rock slopes are multiple. As shown by Lawson the length of the slope is one factor. The sizes and shapes of the blocks of rock and the rate at which they are loosened by weathering in place are other factors. On slopes of less declivity than those controlled by gravity alone the maximum amount of the rill wash partially controls the slope. The relative efficiency of the rill wash on the rock face and the lateral cutting by the graded stream at its base is another factor. Thus it may be seen that the profiles of the rock slopes may vary rather widely with the changes in these various factors.

Near the margin of the range the major streams represent the largest concentration of water and the rills on the slopes of an isolated spur the least. It should be emphasized that desert streams derive a relatively large part of their water from the heads of their valleys, where rain is commonly more copious than around the foothills. In a given storm twice or even ten times as much rain may fall around the mountain peaks as at the edge of the plains. For this reason and because of the well known relations of stream volume, velocity, friction, and power, the floods in the major ravines are vastly more effective than the rills which descend the marginal slopes. Where the hillsides carved by rills or sheet wash meet the floodplains carved by the major streams, there must be an angular break in the profile. The above is an elementary concept, but the fact to be brought out is that this angular break in the profile along a mountain front is due to a difference in the power of the agencies determining it and cannot be due to such processes as rills flowing down the mountain slopes and immediately changing their ability to carry detritus on the gentler slope of the pediment. Finer detritus on the pediment would be transported at a lower angle, as suggested by Bryan (3, p. 57), but some other agency than a rill must be sought to account for the abrupt angular change at a particular point. The transporting power of a rill is controlled largely by its volume and such increases in its velocity as are due to the increase in volume and consequent decrease in the relative importance of friction upon its bed. The volume increases in arithmetical ratio as the water flows down the mountain side. Friction also increases with the velocity.

The writer has found no published explanation of why an abrupt change should take place in the power of such rills and hence in the size of the fragments carried.

To return to Figure 2, first consider the beveled rock surface represented by the curve A-B. If all the intermediate profiles are imagined drawn in, then the line A-B must be a smooth curve determined by the locus of intersection of the rising slope of deposition (B-D) with the retreating rock surfaces which are being carved by the graded streams and the rills respectively. While being formed this surface has been buried to such an extent that streams no longer scour bedrock. This feature is Lawson's *suballuvial bench* which is only partly due to lateral planation by the larger streams. Once formed, the suballuvial bench is not changed, for it is buried henceforth by alluvium. However, as the mountain mass becomes old, the flattening of the stream profiles may extend stream planation outward from the range and regrade the upper margin of the suballuvial bench. It should be noted that the bench is not thereby stripped and brought to view as supposed by Paige (15, p. 445). The regraded part will be a new feature, a facet of the pediment, replacing the suballuvial bench at that point. The pediment and the suballuvial bench are distinct features which should not be confused with each other.

Now let us turn to a consideration of the part of the stream profile above the point where the erosion by floods fails to reach bed rock. From this point, as far up as the stream has reached grade, we have an agency that can no longer cut downward except as grade itself is slowly lowered, but nevertheless has great erosive power. It therefore widens its valley without deepening it. Let us assume that this zone extends from the point B to point X on the profile 5 of Figure 2. This is a surface of planation maintained at a relatively gentle angle (50 to 200 or 300 feet per mile) controlled by the graded streams traversing the plain. There will be a sharp break in slope between this surface and that of the mountain whose angle of slope is determined by the unconcentrated rill wash, gravity and rock structure, as explained above. The surface of planation is being lowered very slowly as the profiles of equilibrium of the streams become gentler. It is being rapidly widened by the side-cutting action of the graded streams. Since it is a surface determined by swinging streams of nearly constant gradient it will always be covered with a nearly uniform veneer of detritus, whereas the suballuvial bench is buried under a detrital wedge which steadily increases in thickness away from the mountains. The surface of planation may be designated by the term that has come into common use for these features, the *pediment.*[2] The pediment is most extensive along the major streams and is in adjustment with the carrying power and load of those streams. It grows mountainward by the progressive shift of this graded portion upstream as the profile of equilibrium is flattened. The stream has been graded in its lower portion for a longer time and hence has been able to widen its valley more extensively there. Each floodplain becomes narrower upstream; hence the "bays" in the mountain front, as described by Davis (4). If the stream is radially divaricate or exists as a single unit and swings across its valley in a greater and greater arc downstream, it should develop what Johnson has termed a "rock fan." But if this stream is anastomosing, as Blackwelder (2, page 137) observes, and as the present writer has noted on several pediments, the convex fan form would not be developed. Further study and accurate measurements of pediments are needed before any definite conclusions on this point will be warranted. One fact that should be noted is that the longer the radius and the less the arc of swing, the less will be the convexity of the graded surface. It is to be hoped that some observer will supply exact data regarding certain instances of this kind.

Let us now consider the factors which determine the extent and character of the pediment developed in a closed basin. If the interrange depression is small and the range is large, the quantity of detritus swept out of the canyon will be large in relation to the capacity of the basin. Hence the surface of the alluvial deposit will rise rather rapidly and will fringe the mountain spurs closely. There will thus be formed a suballuvial bench, entirely concealed, however, by the usual sheet of alluvium which is wedge-shaped in cross section.

Where the valley is wide and the range is narrow and low, the alluvial basin is large in comparison with the mountain range furnishing the detritus and as a result the filling of the basin lags behind the cutting away of the mountain mass. Under such conditions the pediment will become the dominant feature of the plain at an early stage in the cycle of erosion. As explained by Johnson (10) it occupies the space between the wasting mountain and the central area of alluviation in the basin.

---

[2] For the sake of accuracy it seems best to limit the term "pediment" to the more or less continuous plain along the mountain front formed largely by the lateral erosion of streams at grade and only veneered with stream detritus. The suballuvial bench has a steeper slope than the corresponding pediment.

If the basin and range are sharply divided by a steep slope such as a fault scarp, the suballuvial bench covered by its alluvial wedge will be the dominant feature developed early in the cycle, as steep alluvial fans rise against the mountain front. Later in the cycle the pediment will become dominant and will even spread outward from the range as well as into the range. The streams will cut away the upper edge of the previously formed alluvial fans and downward into the underlying suballuvial bench. It is to be emphasized, as Blackwelder (2) has done, that in the later part of the cycle the pediment is the dominant feature of the desert landscape.

In any one basin and indeed in deserts at large the slopes of the pediment should be fairly constant, since they are determined by the grade profile of the streams working under similar conditions. On the contrary, the slopes of the suballuvial bench in the same basin may be highly variable. Where resistant rocks of the mountain spur are being engulfed by the rising alluvium of a main stream excavating softer rocks, the suballuvial bench may be steep opposite the spur in comparison to the slope of the bench along the stream.

In discussing the origin of the plains of the desert it is important to distinguish between the suballuvial bench of Lawson and the pediment of Bryan and Johnson. Johnson (10, page 663) considers Lawson's suballuvial bench and the pediment of Bryan and McGee as synonymous. The present writer has shown that these two types of surfaces planed on rock are different in form and origin. The surface of a pediment must be continually lowered as the grades of the streams traversing it are lowered. This is recognized by Johnson (10, page 662) under the term *regrading*. The surface of a suballuvial bench may be much more irregular than that of a pediment. A pediment has a profile concave upward while a suballuvial bench may be variably concave and convex upward, but is generally convex. Further evidence is needed to reach any conclusions regarding the convex fanlike forms on rock, as noted by Johnson. The suballuvial bench, being almost invariably covered by a sheet of alluvium which does not conform to its surface, is a buried feature that is very seldom if ever revealed to the observer as a part of the desert landscape.

It is the pediment, with which the suballuvial bench has been confused, that is the prevailing type of rock plain in such regions. Wherever a suballuvial bench exists beneath the surface, the visible plain should have the convexities of coalescent alluvial fans, for the bench is carved during the process of aggrading the basin and owes its form to the rise of the alluvial deposit.

SUMMARY.

After reviewing the ideas of previous students of the slopes formed by stream erosion in dry climates, the writer analyzes the development of such slopes in the light of his own field studies. He concludes that the pediment or rock plain is the work of graded streams issuing from the canyons and ravines rather than the rills or sheet floods descending the mountain side, and that the abrupt change in slope between the pediment and the mountainside is due to this difference in agency rather than to a change in the behavior of rills on reaching the bottom of the slope. The writer is doubtful regarding the formation of rock fans as set forth by Johnson. He has been unable to find definite evidence of their presence in certain places where they should be expected.

In this paper it is explained that the suballuvial bench of Lawson and the pediment of McGee and Bryan are features which are different in both form and origin. Of these two only the pediment becomes a part of the topographic surface. The suballuvial bench is normally buried. The distinction between these two, which seems not to have been recognized by previous writers, appears to be essential to an understanding of desert physiography.

BIBLIOGRAPHY.

1. Berkey, C. P., and Morris, Frederick K.: Geology of Mongolia. Am. Museum Nat. History, 1927.
2. Blackwelder, Eliot: Desert Plains. Jour. Geol., **39**, pp. 133-140, 1931.
3. Bryan, Kirk: Erosion and sedimentation in the Papago Country, Arizona. U. S. Geol. Survey Bull., **730**, pp. 19-90, 1932.
4. Davis, W. M.: Basin Range Problem. Proc. Nat. Acad. Science, **XI**, 387-392, 1925.
5. ———: Rock floors in arid and in humid climates. Jour. Geol., **38**, pp. 1-27, 136-158, 1930.
6. ———: Work of sheetfloods. (Abstr.) Geol. Soc. America Bull., **44**, page 83, 1933.
7. Gilbert, G. K.: Report on the geology of the Henry Mountains. U. S. Geog. and Geol. Survey, Rocky Mountain Region, Washington, 1877.

8. Johnson, Douglas: Planes of lateral erosion. Science, N. S., **75,** pp. 174-177, 1931.
9. ———: Rock fans of arid regions. This Journal, 5th ser., **XXIII,** pp. 389-416, 1932.
10. ———: Rock planes of arid regions. Geog. Review, **XXII,** pp. 656-665, 1932.
11. Keyes, C. R.: Rock floors of intermont plains of the arid region. Geol. Soc. America Bull., **19,** pp. 63-92, 1908.
12. Lawson, A. C.: Epigene profiles of the desert. Univ. Calif. Pub. Geol., **IX,** pp. 23-48, 1915.
13. McGee, W. J.: Sheetflood Erosion, Geol. Soc. America Bull., **8,** pp. 87-112, 1897.
14. Ogilvie, I. G.: The high altitude conoplain. Amer. Geol., **XXXVI,** pp. 27-34, 1905.
15. Paige, Sidney: Rock-cut surfaces in the desert ranges. Jour. Geol., **20,** pp. 442-450, 1912.

STANFORD UNIVERSITY,
STANFORD, CALIFORNIA.

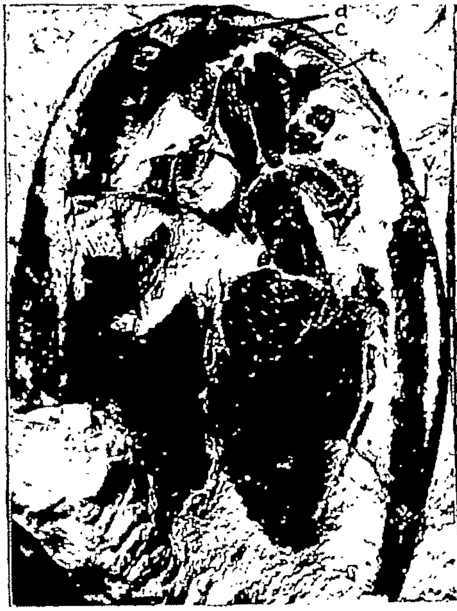
THE OSTRACODERM GENUS DARTMUTHIA PATTEN.

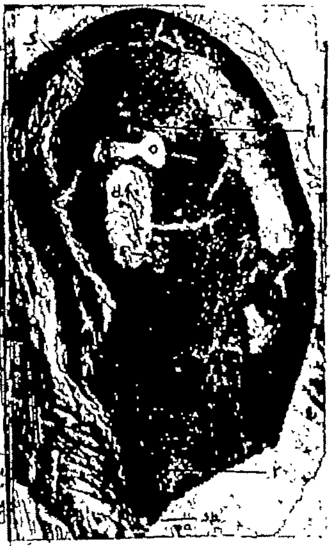
GEORGE M. ROBERTSON.

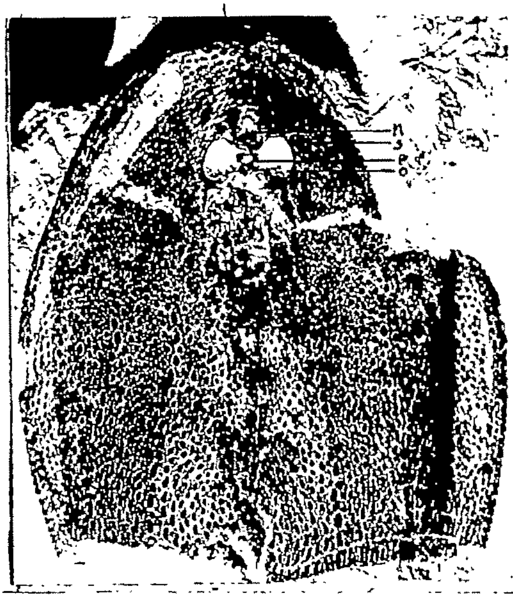
The ostracoderm order Osteostraci has been variously divided into families. The Cephalaspidae and the Tremataspidae are recognized as distinct. *Ateleaspis* and *Astraspis* are variously disposed of. Traquair (1) gave the former family rank, although later (2) he reduced it to a genus of the family Cephalaspidae, a position which Stensiö (3) also takes. Woodward (4) unites *Astraspis* with *Ateleaspis* as Ateleaspidae. Romer (5) gives *Ateleaspis* family rank and ranks *Astraspis* as constituting a family of uncertain position. Stensiö (6) assigns *Astraspis* to the Heterostraci under the Drepanaspidae, while Eastman (7) and Schlosser (8) give it family rank in that same order.

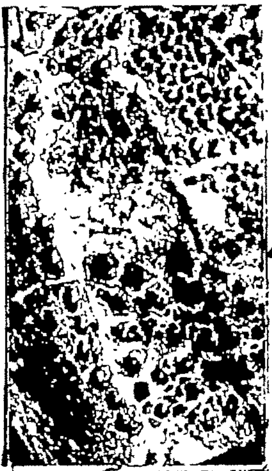
The principal distinctions between the Cephalaspidae and the Tremataspidae are the possession of cornua on the postero-lateral corners of the head and trunk shield in cephalaspids and their absence in tremataspids; and the subdivision of the lateral sensory or electric fields in tremataspids into two short lenticular areas on either side, their persistence as single elongated organs on either side in cephalaspids. Stensiö (6) regards the absence of cornua as implying absence of pectoral appendages such as those of cephalaspids, since these lie in indentations, the pectoral sinuses, produced in the posterior margin of the shield just within the cornua. There are also some differences in the minute structure of the exoskeleton, but with increased knowledge of the variety of forms, especially among Cephalaspidae, these differences become less significant. It will probably happen that in time some new genera of the Tremataspidae will be found which may still further bridge the gap between these families. A family represented by a single genus can hardly be regarded as sufficient basis for broad generalization.

In 1931 Dr. William Patten (9) described a new form, *Dartmuthia gemmifera*, n.g., n.sp., which in some ways is intermediate between the cephalaspids and the tremataspids. Like the Cephalaspidae it has the lateral fields continuous rather than broken, and has a rugose rather than a smooth dorsal shield surface. Like the Tremataspidae it lacks cornua to the shield, and thus presumably had no pectoral appendages. The median, unpaired section of the shield which lies behind the


1


3


2


4

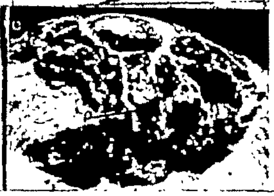

5

Fig. 1. Specimen No. 71. Ventral aspect. x ca. 2. (d) depressed area; (c) centrally-directed process; (t) triangular plates; (v) ventral shelf.

Fig. 2. Specimen No. 70. Dorsal aspect showing ornamentation. x ca. 2. (n) nasal organ; (o) orbit; (p) pineal; (s) circumorbital sensory canal.

Fig. 3. Specimen No. 85. Dorsal aspect. x ca. 1¼. (n) nasal; (o) orbit; (d, f) dorsal field; (l) lateral field; (e) endolymphatic aperture; (s) circumorbital sensory canal; (r) mid-dorsal ridge; (sp) dorsal spine.

Fig. 4. Specimen No. 106. Part of left lateral sensory or electric field showing separate plates over part of the field. Also shows superficial scales surrounding tubercles. x ca. 4.5.

Fig. 5. Specimen No. 94. Dorsal aspect of left sclerotic (sc) and pineal

branchial region and so belongs to the trunk, that section which Stensiö (6) designates as the interzonal part, is long in *Dartmuthia* as in *Trematasp̄is*. The exoskeleton of the dorsal shield differs from that in Cephalaspidae as well as from that in Trematasidae. In cephalaspids the superficial layer is generally smooth and continuous save for grooves or for tubercles, whereas in *Dartmuthia* the superficial layer is broken into minute polygonal areas, almost scale-like, surrounding tubercles which arise from the middle layer (Fig. 4).

The fossils of this genus, as of the Osteostraci in general, usually consist of the anterior portion of the body only. This was encased in bony dorsal and ventral shields. In *Tremataspis* the dorsal and ventral armor was continuous, which accounts for the more frequent occurrence of specimens with both dorsal and ventral surfaces available. In *Dartmuthia* dorsal shields have been much more abundantly preserved, the ventral shield being sutured to a narrow ventral shelf or rim which is continuous with the dorsal shield (Fig. 1). There are no individuals in the collection of something over 300 specimens with this ventral surface completely preserved, even in the post-branchial region. Fig. 1 is a photograph of the most complete ventrum in the collection. In cephalaspids as well, though (3, 6) in many forms the ventral interzonal part was continuous, good ventral aspects are rare. Among the fossils brought back by Doctor Patten on his last expedition to Oesel are about 100 cephalaspids or cephalaspid fragments. Of these only a few show any trace of ventrum and in none thus far worked out has the region just central to the ventral rim been preserved. The shortness of this portion of the ventral shield in cephalaspids may have made preservation more rare.

It appears probable that the Osteostraci were fresh-water forms, the deposits consisting of remains which were carried down stream, suffering considerable damage en route. In some cephalaspids, notably from the Old Red Sandstone formations, the tail region has been preserved (3). In the tremataspids such preservation is rare. In *Dartmuthia* few specimens so far examined have shown this region, and in none has it been at all complete. Since the scales of this posterior region were not interlocked in such fashion as to hold the form together after the soft parts had macerated, and since, if our supposition as to the taxonomic position of the ostracoderms is correct, the notochord was persistent, there would be little chance of this portion of a carcass remaining together and associated with the head and trunk shield during its peregrinations prior to deposit.

The same conditions have brought about the loss of other loosely connected parts, such as the plates which acted as armor over the oralo-branchial chamber on the ventral side of the head, termed by Stensiö (3) the ventral visceral exoskeleton. This lack of preservation has led to uncertainty as to the make-up of this region. In the specimens of *Dartmuthia* in the Patten collection none has this region complete, but a few have some of the plates apparently nearly in place (Fig. 1), permitting comparison with *Tremataspis.* Some specimens of this latter genus have the plates more completely preserved. One in particular in the Patten collection has the anterior median plates together with most of the plates of the left side of this region practically in place. This specimen, as nearly as can be ascertained, formed the basis for Doctor Patten's last reconstruction of *Tremataspis* (10).

The collection of *Dartmuthia* comes from the Island of Oesel (Saaremaa), in Estonia. The horizon is middle Ludlow, upper Silurian. The stratigraphy of this region has been discussed by Luha (11). Some of the specimens were collected by Doctor Patten in the summer of 1930, the rest in the summer of 1932. Thus far I do not distinguish more than one species, *Dartmuthia gemmifera* Patten. There are variations in some features, such as ornamentation, but if two or more of the variable features are studied it will be found that all combinations occur, indicating, in my opinion, simply variations within the species. Other differences such as size seem to grade together as though indicative of age and of those obscure factors which condition size variation among the individuals of a species.

Dartmuthia is a small form, the length of the shield being seldom over 50 millimeters, the width usually under 40. The dorsal shield is ornamented with tubercles (Figs. 2, 4), averaging a trifle over two to the square millimeter on the general surface, each surrounded by small, polygonal, scale-like plates. The tubercles vary from round to elongate, blunt to pointed. The arrangement of the tubercles is variable, possibly sufficiently to be of taxonomic significance. In the anterior portion especially there is some alignment of tubercles (Figs. 2, 3), the lines following the curve of the shield. This is especially marked just anterior and lateral to the nasal eminence. The mid-dorsal line also shows alignment, and in some cases the regions flanking this show the same feature, usually less marked. In some specimens this alignment can be detected over the general dorsal surface. In others the tubercles show little evidence of any arrangement over this general region. The mid-dorsal ridge, usually elevated somewhat, is capped by a line of more prominent tubercles, which commonly become more pronounced posteriorly, while the ridge itself becomes more marked. In some specimens (Fig. 2) short lines of more pronounced tubercles occur here and there on the lateral regions of the dorsum, usually two or three lines on either side. The capping tubercles of the mid-dorsal ridge are sometimes in a single line, sometimes irregular, sometimes double. At the posterior end of the shield is a backwardly and slightly upwardly directed process, the dorsal spine (Fig. 3). The tubercles on this portion may run together to form more massive structures or may be only slightly elongated. The running together of tubercles, either end to end or side by side, is not uncommon, especially in regions where the tubercles are most pronounced or numerous. The dorsal spine varies somewhat in form, being in most cases decidedly triangular, somewhat as in *Kiaeraspis auchenaspidoides* figured by Stensiö (6); in other cases being more spine-like, with a more abrupt origin from the posterior line of the shield, and less triangular, somewhat similar to *Cephalaspis lankestri* (3).

In those cephalaspids in which this portion is well preserved along with the posterior trunk region it has been found that the dorsal crest forms a direct continuation of the median dorsal ridge of the shield, and is thus continuous with the spine. In one specimen of *Tremataspis* (*T. mickwitzi* ?) in the Patten collection a similar situation occurs, the whole structure, in fact, being strongly like that figured by Stensiö (3, p. 53) for *Hemicyclaspis murchisoni.* This portion of the trunk region is insufficiently preserved to be reconstructed in any of the *Dartmuthia* material, although some fragments which may well have been dorsal crest scales or scutes have been found.

Laterally the posterior portion of the dorsal shield shows indications of segmentation (Fig. 2), each segment being separated from the rest of the shield and from its neighbors by shallow grooves. In some cases the tubercles of each segment are elongated and are arranged as a single row, a condition which carries over to the anterior lateral plates or "scales" of the posterior trunk region. A similar segmentation has been noted in a number of cephalaspids, notably *Thyestes* and *Kiaeraspis*.

The tuberculation occurs on the plates which cover the dorsal and lateral sensory or electric fields. These plates are in fact so similar to the general dorsal surface that in some cases it is not possible to find any trace of the lateral fields, especially if there has been lateral compression which has forced this region up to the general surface level. One specimen (Fig. 4) shows the plates over a part of the left lateral field especially well. The structure is like that of the general dorsal surface save that each tubercle forms the center of a separate plate. Were the plates to fuse together the structure would be identical with that seen in the exoskeleton lateral to the field. The pineal plate and the sclerotics (Fig. 5) are also tuberculated on their upper surfaces.

Where the superficial layer of the shield is missing the tubercles show somewhat crenulated margins, actually fine ridges ornamenting their borders and flowing into the general surface of the middle layer. This appearance is most marked on the lateral margins of more elongated tubercles, such as those ornamenting the segmented portions of the shield, the posterior portion of the mid-dorsal ridge, and on the inner edge of the ventral rim, where the ornamentation gives a feather-like appearance to the tubercles. Doctor Patten (9) called attention to this feather-like ornamentation, especially in the region of the ventral surface near the gill openings.

Toward the lateral and anterior margins of the shield the tubercles become more definitely aligned and the lines closer together. Here too the tubercles become elongated and nearly confluent, forming a marginal armor (Fig. 2). The tuberculation continues over the ventral rim, where its character is somewhat altered, the tubercles becoming blunt. In some specimens the tubercles of the ventral rim are aligned, the lines running diagonally outward and posteriorly. In others the lines are not observable.

The ventral rim (Fig. 1) forms a narrow shelf in the trunk region, narrowing abruptly at the posterior end of the branchial area. Anterior to this the branchial pouches modify the contour of the rim, the marginal region becomes more rounded, and the ornamentation becomes throughout similar to that of the dorsal rim. Central to the shelf in the post-branchial region the ventral surface is ornamented with polygonal areas or plates with crenulated borders. These polygonal scales or plates (Fig. 1) are largest toward the mid-ventral line, where they may measure up to two millimeters across. Toward the lateral margins they become smaller, eventually giving place to the flattened tubercles of the central portion of the shelf. There the minute polygonal scales of the superficial layer come in between the tubercles.

It is of interest that the polygonal scales of the ventrum appear to grade into the flattened tubercles of the ventral shelf. Fig. 1 shows this slightly. In some specimens this transition is very apparent. The plates are flattened and thinner, so thin that in many cases the reticulated structure of the skeletal layer immediately beneath them is quite visible. In both scales and flattened tubercles the polished layer strips or chips off very readily and discloses very similar structure underneath. The dorsal tubercles differ from both in more massive structure. They do not scale off readily, but break with an irregular fracture. However, if one follows the ornamentation the tubercles of the general surface grade into those of the dorsal rim, which in turn are carried over onto the ventral rim.

Such a transition suggests either that the continuous dorsal armor studded with tubercles may have arisen by fusion of scales or plates such as those of the ventrum, the middle layer becoming more dense and the polished portion becoming reduced to tubercles, accompanied by development of the minute scales which surround the tubercles, or that the reverse procedure has been followed. The separate plates over the lateral fields might be regarded as a transition stage, in which the denser middle layer has encroached on the polished portion and in turn been coated with the minute scales of the superficial layer, the separate plates or scales not yet having fused.

A somewhat similar situation exists in *Hemicyclaspis* (3) in which the post-branchial ventrum is not continuous but is made up of scales. *Ateleaspis* might represent another stage, near the beginning or the end of such a series, since in it the dorsal shield also consists of separate plates or scales (1, 2).

The ventral surface of the oralo-branchial region (Fig. 1) was as in Tremataspidae and Cephalaspidae, probably having been closed by a flexible membrane in which were embedded the plates which served as armor over the oralo-branchial chamber. In most fossils the plates are lost. In a few specimens some of them are preserved, and they appear to resemble closely those of *Tremataspis* figured by Doctor Patten in his last paper (10). The inner edge of the anterior rim bears in the mid-line a small triangular process, ornamented with tubercles of relatively small size. This is directed backward, and in the fossils is slightly depressed. A similar depressed area occurs in both cephalaspids and tremataspids. On either side of this, separated from the triangular process by about its own width, is a centrally directed process. Lying in the mid-line in this region are two triangular plates, about ten millimeters in length, about three millimeters in basal width. They are directed posteriorly and the basal width of the two together fills the gap between the central ends of the inwardly directed processes. These triangular plates are ornamented with polygonal scales similar to those of the general ventral surface. These are largest toward the center of each plate, growing smaller and more tubercle-like toward their margins. The other plates of the oralo-branchial region were similarly ornamented, as can be seen in Fig. 1. They apparently were quite similar to the corresponding plates of *Tremataspis*, although they are not sufficiently closely in place to allow complete reconstruction of the region.

The external gill apertures are similar to those of *Tremataspis* and *Cephalaspis*, a number of small openings (at least five), in a series running diagonally inward and backward at the border of the post-branchial region, and indications of probably four more along the lateral margin of the oralo-branchial chamber. The endoskeleton of the oralo-branchial region of the dorsal shield shows, as it does in cephalaspids, what lend themselves readily to interpretation as gill pouches.

On the dorsal surface (Fig. 3) three sensory or electric fields are situated somewhat as in *Cephalaspis*, i.e. a single elongated lenticular field, 8 to 10 millimeters in length, about 4 millimeters at its greatest width, directly behind the pineal region, and a pair of lateral fields about 20 millimeters long by 3 to 4 millimeters wide. The dorsal field does not include the openings of the paired canals interpreted as housing the endolymphatic ducts. These apertures lie just lateral to the posterior end of the dorsal field (Figs. 2, 3). The field is thus somewhat longer than that of *Tremataspis*, in which the canal openings lie posterior to the field. In most cephalaspids (3) the canals open within the dorsal field.

The lateral fields are less extensive than in cephalaspids. They commence lateral to the anterior part of the infra-orbital sensory canal groove and extend about half way back on the shield. The innervation of these fields is, so far as can be determined at present, practically identical with that in the cephalaspids. None of the specimens thus far uncovered shows the degree of completeness of these structures shown by some of the cephalaspids figured by Stensiö (6, Pl. 49), but sufficient is preserved to demonstrate that in essentials the *Dartmuthia* lateral fields were innervated by the same nerve elements as were those of the cephalaspids. In cephalaspids there are six branches, of which the two anterior remain together until they near the inner border of the field. The anterior branches in *Dartmuthia* are similarly associated, separating practically at the border of the lateral field, as in the Kiaeraspinae (3). The other branches show a distribution similar to those of *Cephalaspis*, but in no case thus far worked out has it been possible to ascertain the exact number of branches. There are at least five altogether, and in a few cases indications that a sixth may have been present.

The lateral fields are, as indicated previously (Fig. 4), covered by small plates of typical exoskeletal structure. They are in turn underlain by the endoskeleton. Since the skeletal relationships of *Dartmuthia* are the same as in *Cephalaspis*, including a subaponeurotic vascular plexus between the exo- and endoskeleton (6), it seems probable that the exoskeleton belongs to the corium and that the lateral fields are of similar origin.

The orbits (Figs. 2, 3) lie close together as in the other families of this order. They are oval in form, the long axis longitudinal. As in Cephalaspidae and Tremataspidae, ossified sclerotics are present (Fig. 5). The upper surface of the sclerotics is tuberculated.

Between the orbits lies the pineal plate. This plate is rarely preserved in any of the ostracoderms. It has been found complete in but one specimen of *Dartmuthia* (Fig. 5), out of approximately 400 examined, a good share of which have the orbital region fairly well preserved. The pineal plate is cylindrical, with upper and lower foramina. In general form it is like that in cephalaspids (3) and tremataspids. It is tuberculated on its upper surface.

The naso-hypophysial aperture is located just anterior to the pineal plate, separated from it by about the same distance as is the dorsal field (Figs. 2, 3, 5). The aperture is located in the bottom of a depression which occupies the top of a slight eminence. The state of preservation of the material makes it uncertain what amount of variation occurs in the form and ornamentation of this region. The general condition found in specimens is that the aperture is on a slight elevation in the center of a cup-shaped depression whose margins are in turn slightly elevated. On either side of the center elevation the floor of the pit is especially depressed. In some specimens the cup-shaped depression is somewhat triangular, with one point forward. In a number of specimens the middle of the posterior rim of the pit is occupied by a large, horseshoe-shaped tubercle, with the points of the shoe downward and forward, the aperture, which is slit-like, piercing the open part of the shoe and extending from that along the floor in the mid-line. It seems probable that this type of structure may have been present in the specimens in general, but in many cases the posterior rim of the depression is eroded or broken. The specimen photographed for Fig. 2 shows such a tubercle, although the illustration does not bring it out. In Fig. 5 the depression can be seen, and at its posterior edge the broken front of the horseshoe.

In 1903 Doctor Patten (12, 13) described the lateral line system of *Tremataspis*. The lines which are found on the dorsal surface of the *Tremataspis* shield consist of broken grooves, a series of dashes. One set of these encircles the orbital region, the two halves meeting or nearly meeting anterior to the nasal opening. This canal Doctor Patten termed the circumorbital. In the cephalaspids the grooves appear to be more nearly continuous where they are found, but the whole system is either less fully developed than that of *Tremataspis* or may have been more superficially situated (3, 6).

In *Dartmuthia* little of the system is preserved. The only part which can be certainly demonstrated is the circumorbital, or in the terminology of Stensiö (6), the infraorbital (Figs. 2, 3). This is very similar to that shown in *Hemicyclaspis* (3, Fig. 23), running very close to the orbits, then forward and curving inward some distance anterior to the nasal opening. It does not flare outward anterior to the orbits as in the specimen figured by Stensiö. In some specimens of *Tremataspis* the two sides of this groove may be united across the anterior end; in some others they stop short of this; while in others the system on one side may be continued to the mid-line and its mate stop short of this point. In the *Dartmuthia* material showing this portion of the system a similar situation exists, although it is more difficult to be sure of the termination of the lines than in *Tremataspis*. In some cases it has been possible to follow a connection between the lines. As in cephalaspids, the lateral line system is usually exhibited only in those specimens in which the superficial layer of the exoskeleton is preserved or in the counterpart which has stripped off from such specimens.

The exoskeleton of the dorsal shield consists of three layers as it does in the other families of the order. The superficial layer consists of glossy scales (Figs. 2, 4), darker in the center. The tubercles protrude through this layer, so that each tubercle is surrounded by a series of the scales. Both scales and tubercles are stippled with minute indentations. Whether the superficial layer is of enamel has not been ascertained.

The middle layer is heavy. It consists of bone, as usual. The tubercles grow out from this layer. The separation between this and the basal layer is not always demonstrable, but where it shows it indicates a basal layer somewhat thinner than the middle layer, divided into polygonal areas with raised borders.

The thickness of the exoskeleton varies as it does in *Cephalaspis*, being thickest around the margin, especially the anterior rim, thinnest anterior to the nasal eminence and lateral to the orbits, between them and the lateral fields. The basal layer appears to be made up of fibrous laminae as in cephalaspids.

Beneath the exoskeleton lies an endoskeleton. As in cephalaspids (6), perichondrial bone of this endoskeleton lines the labyrinth cavity, the orbits, the canals for nerves and vessels which traverse the endoskeleton, the oralo-branchial chamber, and the brain case. Thus it is possible to make out many details of structure such as the form of the gill pouches, the distribution of nerves and vessels, the form of the labyrinth cavity, and in a few instances, some features of the brain case. In one fossil, for example, a good part of the cerebellum is exposed, and it is hoped that this specimen will show further portions of the posterior region on further dissection.

The posterior portion of the trunk and the tail are not preserved in any degree of completeness. Nevertheless fragments of that region are available, and from information derived from these fragments enough can be determined to show that this region is essentially like that in *Tremataspis* and *Cephalaspis*. The anterior portion of this post-shield region continues the ornamentation of the segmented portion of the shield, i.e., each of the "scales" or plates was ornamented with a row of low, elongated tubercles. No positively identifiable plates of the dorsal ridge just posterior to the dorsal spine have been found, although some fragments may be such plates.

On one specimen a single posteriorly situated dorsal fin and a heterocercal caudal are incompletely preserved. The specimens showing traces of this region are distorted, making orientation difficult. It appears safe to state that there is on either side a lateral row of scales or plates, with a dorsal row of shorter plates or scutes, fairly marked ventro-lateral ridges, and on the ventrum diagonally arranged rows of smaller scales, each row directed inward and forward to meet its mate from the opposite side in the mid-ventral line.

I wish to express my gratitude to Dr. B. M. Patten for placing the material of his father's collection in my hands for description, also to Mr. H. H. Barrett, Dartmouth College photographer, for producing the figures accompanying this paper. Finally, I wish to acknowledge my debt to the late Dr. William Patten. His devotion to the task which he set himself as a young man was responsible for the assembling of one of the outstanding collections of these primitive armored fishes in the world. An artist of no mean ability, an ingenious technician, a tireless worker, his was the skill and patience which is largely responsible for the preparation of the fossils on which this description is based. As he left practically no notes on the material as he prepared it, full responsibility for interpretation of structures rests on me, and errors which that involves are of my own making.

BIBLIOGRAPHY.

1. Traquair, R. H.: Report on Fossil Fishes collected by the Geological Survey of Scotland in the Silurian Rocks of the South of Scotland. Trans. Roy. Soc. Edin. 39, 834, 1899.
2. ———: Supplementary Report on Fossil Fishes, collected by the Geological Survey of Scotland in the Upper Silurian Rocks of Scotland. Trans. Roy. Soc. Edin. 40, 883, 1905.
3. Stensiö, E. A.: The Cephalaspids of Great Britain. 1932.
4. Woodward, A. S.: Text-book of Palaeontology. Von Zittel. Second English Edition. 1932.

5. Romer, A. S.: Vertebrate Paleontology. 1933.
6. Stensiö, E. A.: The Downtonian and Devonian Vertebrates of Spitsbergen. Part I, Family Cephalaspidae. 1927.
7. Eastman, C. R.: Fossil Fishes in the Collection of the United States National Museum. U. S. Nat. Mus. Proc. 52, 1917.
8. Schlosser, M.: Pisces, in Zittel's Grundzüge der Paläontologie. Abt. II, Aufl. 4, 1923.
9. Patten, W.: New Ostracoderms from Oesel. Science 73, No. 1903, 671, 1931.
10. ———: Foundations of the Face. Scientific Monthly 35, 511-21, 1932.
11. Luha, A.: Ueber Ergebnisse stratigraphischer Untersuchungen im Gebiete der Saaremaa-(Oesel-) Schichten in Eeste. Tartu 1930.
12. Patten, W.: On the Structure and Classification of the Trematapsidae. Mem. de l'academie des Sc. de St. Petersbourg 13. 1903.
13. ———: On the Structure and Classification of the Trematapsidae. Amer. Naturalist 36, 379-93, 1902.

Dartmouth College,
Hanover,
New Hampshire.

KERATOPHYRES OF EASTERN OREGON AND THE SPILITE PROBLEM.

JAMES GILLULY.

PART II.

THE MAGMATIC OR POST-MAGMATIC AGE OF THE ALBITE.

The question of magmatic versus metasomatic (either autometamorphic or exomorphic) origin of the albite of the spilitic rocks has two aspects: that referring to the saturated keratophyres and the siliceous quartz keratophyres and that referring to the subsiliceous spilites and albite diabases.

The production of siliceous rocks with notably high soda-potash ratios by crystallization differentiation has been discussed most suggestively by Goldschmidt,[1] in connection with the trondhjemitic intrusions of western Norway. Here it is postulated that in hydrous magmas there exists a tendency for an early formation of biotite, thus leading to a relative impoverishment in potash at given silica content of the rest-magma as compared with the normal (less hydrous) magmas. Any process separating the rest-magma from its earlier crystals must then introduce the possibility of highly sodic, potash-poor rocks. Goldschmidt offers this mechanism for the opdalite-trondhjemite differentiation series, pointing out a widespread occurrence of granodioritic rocks in orogenic belts, and suggesting that the geosynclinal sediments of these belts may have contributed the water that effected this trend in differentiation. It may be significant, in this connection, that plutonic rocks of high Na/K ratio (low k value of Niggli) are found in many of the spilite localities of the world, notably New South Wales, the Caledonian chain of Norway and Scotland, the Sierra Nevada, and eastern Oregon. The differentiation course elaborated by Goldschmidt seems well established even though the adequacy of the environmental factors stressed by him as determining it seems open to question. The rock sequences in many regions appear to demonstrate the frequent formation of siliceous sodic magmas and there seems little reason to question a magmatic origin of the oligoclase in the oligoclase keratophyres, these being quite expectable derivatives of a trondhjemitic differentiation series. The more albitic keratophyres, too, may well be in part magmatic as is suggested by the occurrence of volcanic glass with the composition of soda-rhyolite,[2] but at least many of them show evidences of replacement of earlier more calcic feldspars. This albitization in keratophyres has been noted by many workers[3] and has almost certainly occurred in the eastern Oregon area. (See page 341.)

---

[1] Goldschmidt, V. M.: Stammestypen der Eruptivgesteine: Vidensk. Skr. Mat. Naturwiss. Klasse I, No. 10, 1922.

The idea that the albite of the less siliceous spilites and especially of the albite diabases is largely, if not wholly, metasomatic rests upon mineralogic evidences such as partly replaced labradorite or andesine residua, upon deductions from descriptive petrography, and upon theoretical physical-chemical considerations.

Residua of more anorthic feldspars are reported in spilites or albite diabases or both from New South Wales,[4] Mauretania,[5] Cornwall,[6] Devonshire,[7] Derbyshire,[8] Scotland,[9] Wales,[10] Germany,[11] and Sweden,[12] and occur in the eastern Oregon rocks in small but significant amount. (See page 339.)

Both experimental evidence and general petrographic experience point to the improbability of magmatic albite occurring in ophitic relation with augite indicating crystallization earlier than or simultaneous with the pyroxene. The work of Bowen[13] on the physical chemistry of the system albite-anorthite-diopside has been cited by Eskola[14] as demonstrating (since the albite diopside eutectic lies near 97% Ab) the high improbability that albite could crystallize earlier than pyroxene as seemed to Eskola to be indicated by the ophitic texture. This extreme interpretation of the paragenetic significance of the ophitic texture is certainly open to debate[15] and it appears highly probable that the pyroxene and feldspar of ophitic rocks crystallized simultaneously. The analyzed albite diabase from the Poorman mine (Column 6, Table 1), with excellent ophitic texture, carries modal albite not more calcic than An_4 and practically free from zoisite or epidote. Such epidote as occurs in the rock is in the chlorite pseudomorphs after augite, and not in the feldspar. Since there are hornblende and titanite (leucoxene) present in this rock and normative mafics are calculated as being lime-free, the normative feldspar (approx. An_{20}) is not representative of the model feldspar of the rock. The conclusion seems warranted that the simultaneous crystallization of feldspar of the present composition, and augite in this rock would be quite incompatible with reasonable extrapolation from the physical chemistry of the simple system worked out by Bowen. This is all the more probable inasmuch as the boundary curve between the feldspar and pyroxene fields would be, in natural magmas, still further displaced toward the albite end by the presence of water, as albite is much more soluble in water than diopside.[16] It is true, as mentioned by both Eskola and Sundius,[17] that the presence of iron in the pyroxene must tend to counteract this displacement of the boundary, but, although quantitative data are lacking, it seems utterly incapable of altering the boundary curve enough to permit crystallization of the albite earlier than or simultaneous with the pyroxene.

---

[2] Knopf, A.: Review of Bowen's "Evolution of the igneous rocks": This Journal, vol. 17, p. 380, 1929.

[3] Benson, W. N.: op. cit., p. 599 ff., 1915.
Flett, J. S.: The geology of Knapdale, Jura and Kintyre: Mem. Geol. Surv. of Scotland, pp. 92-93, 1911.
Thomas, H. H., and Jones, O. T.: The Pre-Cambrian and Cambrian rocks of Brawdy, Hayscastle and Brimaston, Pembrokeshire: Geol. Soc. London Quart. Jour., vol. 68, pp. 385-386, 1912.
Stamp, L. D., and Wooldridge, S. W.: The igneous and associated rocks of Llanwrtyd (Brecon): Geol. Soc. London Quart. Jour., vol. 79, p. 41, 1923.
Sundius, N.: op. cit., p. 461, 1916.
Vogt, Thorolf: Sulitelmafältets geologi o petrografi: Norsk Geol. Unders. No. 121, pp. 492-493, 1927.
Nolan, T. B.: personal communication respecting the Tonopah district, Nev.
Lehmann, E.: op. cit., pp. 562, 576, 582, 591, and elsewhere.

[4] Benson, W. N.: op. cit. Proc. Linn. Soc. N. S. W. 1913, p. 667, op. cit., 1915, p. 142.

[5] Du Parc, L. and Pearce, F.: Sur les andésites et les basaltites albitisées du Cap Marsa: Comptes Rendus, vol. 130, p. 96, 1900.

[6] Flett, J. S. and Hill, J. B.: op. cit. (Geology of the Lizard and Meneage), p. 186.

[7] Flett, J. S.: op. cit. (Newton Abbot), p. 60, 1913.

[8] Sargent, H. C.: op. cit., p. 13.

[9] Balsillie, D.: op. cit., pp. 111, 125 and elsewhere.

[10] Greenly, E.: op. cit. (Anglesey), p. 73, 1919.
Wells, H. K.: op. cit. (Rhobell Fawr), pp. 523-524, 1925.
Williams, Howel: The geology of Snowdon, North Wales: Geol. Soc. London Quart. Jour., vol. 83, pp. 406-407, 1927.

[11] Heineck, Fr.: Die Diabase an der Bahnstrecke Hartenrod-Ubernthal bei Herborn: Neues Jahrbuch Beil. Bd. 17, p. 91, 1903.

[12] Sundius, N.: op. cit., 1916, pp. 448, 461.

---

[13] Bowen, N. L.: The crystallization of haplobasaltic, haplodioritic, and related magmas: This Journal, vol. 40, pp. 161-185, 1915.

[14] Eskola, P., op. cit., pp. 88-89.

[15] Fenner, C. N.: The crystallization of a basaltic magma from the standpoint of physical chemistry: This Journal, vol. 29, pp. 217-234, 1910.
Bowen, N. L.: The evolution of the igneous rocks, p. 67, Princeton, 1928.
Sundius, N.: op. cit., 1930, pp. 12-13.

[16] Eskola, P.: op. cit.

[17] Sundius, N.: op. cit., 1930, pp. 13-15.

The selective replacement of calcic cores of feldspar by albite is decidedly opposed to a primary magmatic age of the albite in rocks showing this feature, as pointed out by Bailey and Grabham and Dewey and Flett.

A still further argument against the interpretation of the albite of albite diabase as primary is the statistical one. The overwhelming majority of ophitic rocks contain plagioclases no more sodic than labradorite, or calcic andesine with augite. In igneous rocks with more sodic feldspars, such as oligoclase-andesine or oligoclase, the common mafics are hornblende and biotite, and the ophitic texture is either entirely absent or extremely rare. No albite rocks except albite diabase and spilite have this texture, and, in view of its absence in rocks whose feldspars are intermediate between albite and calcic andesine, it is reasonable to doubt the magmatic origin of the albite. Such albite rocks as are regarded as of magmatic origin, aside from the spilites and albite diabases, that is, the keratophyres, comendites, helsinkites,[18] and some albite granites, contain epidote, chlorite, biotite, or amphiboles, but no augite, though in some alkaline rocks aegirine-augite occurs. They clearly belong to more differentiated magmas. It seems unlikely that the same feldspar, albite, should be of magmatic origin in rocks varying so widely in composition, when the usual relation is to find the composition of the feldspar as a rough measure of the silica content and hence of the stage of differentiation.

This is especially striking when consideration extends to the metamorphic rocks, for in them as well as in igneous rocks, the composition of feldspar varies with the mafic minerals present, albite being the characteristic feldspar of green-schists, whereas andesine or some closely related feldspar is the common one in amphibolites and labradorite occurs in some pyroxene hornfels.

For all these reasons it is extremely probable that the albite of albite diabases is not primary and, if this is true, there is every reason to doubt the primary origin of the albite in spilites in general. Evidence has been presented (see page 342) to show that the albitization represented in the diabases and spilites of the Permian greenstones of eastern Oregon has also affected the more siliceous rocks of the formation. While it cannot be absolutely proved, the evidence suggests strongly that the keratophyres and quartz keratophyres have also been widely albitized by hydrothermal solutions.

---

[18] In this connection it may be pointed out that the type helsinkite is most probably a hydrothermally metamorphosed rock whose albite and epidote are replacement products. See Mellis, O., Zur Genesis des Helsinkits: Geol. Fören, Forhand., Bd. 54, pp. 419-435, 1932.

THE TIME OF ALBITIZATION.

Having thus concluded that the spilitic rocks are not derived from an independent magma and that the basic members as well as many of the siliceous members have almost certainly undergone post-magmatic albitization, the question of the date of the albitization must be considered. This is a very elusive matter, for competent criteria are difficult to establish and apply.

The extremely suggestive paper of Bailey and Grabham,[19] illustrates the difficulty well. The demonstration of the albitization seems conclusive, and its local effect on the groundmass feldspars places its date as later than the consolidation of the groundmass, while it is apparent that mere weathering was not responsible for it. Vesicles in the lava are lined with albite and joined by albite veins which contain crystals in optical continuity with albitized feldspars of the rock. The acceptance of autolytic alteration by hydrothermal solutions residual from the consolidation of the lava rests on more direct evidence than this, although the sporadic and partial albitization of these rocks seems quite in keeping with such a postulate, especially in view of the similarity of the albitic veinlets to the segregation veins of many of the quartz dolerites of the Scottish Permian.[20]

The albitization of the Devonian spilites and albite diabases described by Dewey and Flett[21] was complete prior to the intrusion of the Armorican granites which altered the spilites to hornfels and produced labradorite feldspars at the expense of the earlier albite. The fact, advanced as evidence of a date earlier than the orogeny, that albite crystals broken and sheared by the tectonic movements remained unhealed is not conclusive, as comparable results are common features of metasomatism in sheared rocks, yet it may be granted, from the localization of the alteration and its frequent association with adinoles and cherts, that it closely followed the consolidation of the rocks.

---

[19] Bailey, E. B., and Grabham, G. W.: op. cit., pp. 252-253.

[20] Falconer, J. D.: The igneous geology of the Bathgate and Linlithgow Hills: Roy. Soc. Edinburgh Trans. vol. 45, p. 133, 1906.

[21] Dewey, H., and Flett, J. S.: op. cit., pp. 205-207.

However, this is far from asserting that the alteration was autolytic in the sense that each flow or sill contained within itself the solutions producing the albitization.

Lehmann has shown that the albite-chlorite-quartz alteration of some of the keratophyres of Nassau was the last stage of the igneous history and followed some of the brecciation undergone by the rocks.[22]

In eastern Oregon, direct evidence as to the date of albitization is very limited. In some of the pyroclastics, andesite fragments occur closely associated with quartz keratophyre and keratophyre fragments, suggesting but lacking much of proof that some of the albitization occurred in the neck of the volcano prior to the ejection of the breccia. On the other hand, flow rocks contain albite lining their vesicles, which seems to prove that albitic solutions were present in the surface flows after their chilling. The occurrence of albite granite, intrusive into these deformed albitic greenstones, and itself most probably a product of post-magmatic metasomatism,[23] indicates that long after the surficial (Permian) volcanism and possibly in Triassic time, albitic hydrothermal solutions were permeating the rocks of the region in great volume. The suggested link (in their common richness in soda) between the Permian keratophyres and spilites and the albite granite may be grounds for placing the intrusions in immediate post-Permian time, but only if the albitization of the lavas was penecontemporaneous with their extrusion. Whether or not this is true, the intrusions were originally hornblendic quartz diorite not particularly soda-rich prior to their albitization—showing that a single magmatic evolution would hardly account for a progression from soda-rich lavas to non-sodic intrusions and back to soda-rich intrusions again. Similar anomalies were encountered by Beskow in his studies in Lappland.[24] In view of the demonstrable post-magmatic albitization in the albite granites and meta-andesites and the highly probable albitization of the spilites, diabases, and quartz keratophyres as well, the rather daring hypothesis that all the albitization was later than the quartz diorite intrusions becomes attractive. At any rate, it seems probable that most if not all the albitization of the volcanic rocks followed their complete consolidation.

---

[22] Lehmann, E.: op. cit., p. 591.

[23] Gilluly, James: Replacement origin of the albite granite near Sparta, Oregon: U. S. Geol. Survey Prof. Paper 175-C, pp. 65-81, 1933.

[24] Beskow, G.: op. cit.

THE SOURCE OF THE ALBITIZING SOLUTIONS.

Many theories have been advanced to explain the albitization of the spilitic rocks. It is the purpose of the present section to examine these theories and determine, if possible, their validity.

The oldest theory, that of Termier, in which percolating meteoric waters are the agents, cannot account for the albitization of rock masses as large as the Kiruna or eastern Oregon greenstones nor, as has been noted by Backlund,[25] for intimately associated albitic and non-albitic rocks, though it may possibly apply on the small scale proposed by Termier.

The theory of regional saussuritization with selective removal of the lime from the feldspars, although it has been abandoned by its inventor, Sundius, is not to be lightly disregarded. It is clearly not applicable to large bodies of uniform composition, though it may well account for small albite-rich bodies associated with complementary epidote-rich rocks. The fact that, under low temperature conditions of rock formation, it is the rule for plagioclase to break down into albite plus some other mineral,[26] is in itself suggestive that regional metamorphism may sometimes bring about the albitization of considerable rock bodies.[27] On the whole, however, it is the habit of saussuritization to produce epidote or zoisite in the altered feldspar concomitantly with the albite. The retention of the ophitic texture of many albite diabases is evidence that any chemical changes they have undergone have been essentially metasomatic, so that albite has been introduced in equivalent volume to the anorthite expelled. This seems to preclude a simple driving out of anorthite in solution as an adequate explanation for the albite of these rocks. Nevertheless, the process may have been locally effective.

Authigenous hydrothermal agencies of albitization have been appealed to by Bailey and Grabham, Dewey and Flett, Wells,

---

[25] Backlund, H. G.: op. cit., p. 58.

[26] See Eskola, P.: op. cit., p. 91.

[27] A variant of this view has been put forth by J. W. Evans (discussion of paper by C. E. Tilley, The metamorphosed rocks of the Start area: Q. J. G. S., vol. 79, p. 203, 1923), who believed the albitization of the igneous and sedimentary rocks of North Cornwall might be due to pressure alteration of basic rocks, by which the Ab of the plagioclase passed into solution and ultimately modified the composition of adjacent rocks. According to this view the albite has migrated; in Termier's and Sundius' older view, the anorthite has migrated and the albite is residual.

Eskola and Backlund, although they differ as to details of the composition of the effective solutions. According to the concept of these writers, the unusually hydrous and soda-rich magma consolidated upon eruption with the formation of intermediate plagioclase and augite, with enrichment of the residual magmatic solutions in H_2O, Na_2O, SiO_2, and more or less CO_2. These solutions, at low temperatures, reacted with the earlier crystallized minerals, replacing the more calcic plagioclase with albite and commonly altering the mafic minerals to hornblende and chlorite. Thus, although the aggregate magma was more than usually sodic, it did not make the primary feldspar as sodic as possible, but retained the alkalies in solution to low temperatures—below the stability field of the first feldspars. Indeed, the statement has been made by Wells[28] that spilites, far from being altered rocks, represent their parent magma far more closely than do normal basalts. Wells thinks that a necessary condition for the retention of the residual solutions in intimate contact with the rock is the rapid formation of an impervious skin which impounds the residual liquids. The effectiveness of the quickly-chilled borders of the pillows in serving as impermeable membranes has been seriously questioned on the ground of their weakness under tension, as demonstrated by continued cracking of earlier pillow skins, and extrusion of new pillows.[29]

The most fundamental objection to the autolysis theory, in the sense that the albitizing solutions are strictly indigenous to the individual flows or sills that are albitized, appears to be the quantitative difficulty. One may readily grant the indigenous character of the segregation veins in diabase described by Falconer and those in Cornwall and Devon described by Dewey and Flett—these seem to be of an order of magnitude expectable of deuteric solutions—but for entire masses of albite diabase, locally several scores of feet thick, to have their mass alterations (demonstrably on a huge scale) caused by residual self-contained solutions seems to require volumes of solution whose presence if entirely indigenous would be expected to be revealed by vugs, comby cavities, and other evidences of the volume they occupied while the rock was solidifying. It must be remembered that the evidence generally points clearly to the reactions being younger than the consolidation of the groundmass and that these diabases commonly contain 60 per cent or more of feldspar that can in many cases be demonstrated to have been originally labradorite. To assume merely residual autogenous solutions as responsible for bulk alterations so pronounced as these is to appeal to them on a scale of entirely different order of magnitude from that commonly recognized as attributable to residual solutions, e.g., the formation of myrmekite, mild chloritization, etc., in plutonic rocks.

---

[28] Wells, A. K.: op. cit., 1923, p. 71.
[29] Beskow, G.: op. cit., pp. 286-288.

The contrast can be illustrated by a rough computation, using the rocks of Ballantrae as examples.[30] The glassy labradorite-rock which Balsillie calls "pre-spilite" has the partial composition given below:

Partial analyses of "pre-spilite" and average of two albite diabases from Ballantrae, South Ayrshire.

B. E. Dixon, Anal.

	Pre-Spilite	Albite diabase	Difference %	Difference×.03 (g. per cc.)	
SiO_2	47.01	46.98	— .03	negligible	
Al_2O_3	18.07	12.63	—5.44	....	—.163
Fe (all as FeO)	9.83	14.10	+4.27	+.128	....
MgO	3.17	4.88	+1.71	+.051	....
CaO	10.00	8.67	—1.33	....	—.040
Na_2O	3.46	4.44	+ .98	+.029	....
K_2O	.63	.78	+ .15	negligible	
TiO_2	2.94	4.09	+1.15	.034	....
	95.11	96.57		+.242	—.203

The last columns show the weight, in grams, of the material transferred to and from 1 cc. of the "pre-spilite" in order to produce the average albite diabase, assuming sp.gr. 3.0 for the rocks. The totals of these columns indicate that, if the alteration were indigenous, 1 cc. of this representative pre-spilite must have contained, *after* its crystallization was complete,[31] sufficient solution to permit exchange by reaction with the enclosing rock of about one-fifth g. of TiO_2, FeO, MgO, and Na_2O for somewhat less Al_2O_3 and CaO. Even under the most liberal allowances for unknown solubilities at high temperatures (and pressures which may have existed in many extrusive spilites due to their submarine locus) it is surely beyond all likelihood that the solutions could be concentrated sufficiently to occupy as little as 1 cc. volume; a more probable figure would be several times this volume. If solutions in anything like such volumes were retained in a lava until it became wholly crystalline before reacting on it, at this stage the rock must have had a porosity approaching 50 per cent and even granting liberal increase in mineral volume due to chloritization, etc., it is incredible that the escape of the solutions should not be revealed by collapsed vugs, loose crystal meshes or the like. The changes in mass composition involved in producing spilites from "pre-spilites" like that at Ballantrae (certainly a conservative example because of the slight changes in soda content), seem clearly to call for volumes of solution far beyond the limits permissible on the assumption that each spilite flow carried within itself the solutions that caused its mineralogic and chemical transformation. The changes are so profound as to compare in magnitude not to such comparatively trivial phenomena as myrmekite formation, segregation veins in diabase, and the like, all of admitted deuteric origin, but to such large-scale processes as sericitization of igneous bodies or pegmatization of schists. If it be granted that in most cases the albitization of the spilites and albite diabases followed soon after their emplacement, it seems that the quantitative factors require the altering solutions to be not indigenous but of external source.

---

[30] Balsillie, D.: op. cit., analyses on pp. 111 and 126.

[31] This statement is made in a general way, using the "pre-spilite" as representative of basalts elsewhere completely crystalline and disregards the fact that the particular example analyzed is partly glassy. See Balsillie.

Beskow's theory,[32] that the alterations are due to combined action of the residual watery solutions of the lava and the sea-water retained in intimate contact with the lava by the pressure of the superincumbent sea water, seems preferable to the simple theory of indigenous alteration. He starts from the premise that the extruded spilite lava is practically a normal basalt, but owes its present composition to low temperature saussuritization by permeating heated sea water. The pillowy and vesicular submarine lavas have about the maximum contact surface exposed to sea water which, through boiling, must become enriched in Na and as the temperature falls must permeate the rocks intimately. This brings about decomposition of the feldspar, the production of albite, chloritization of the mafics, and possible extraction of Ca and K with introduction of Na. No great change in bulk composition is postulated.

Beskow's theory is very attractive and may indeed be adequate to explain some spilites. Its principal weakness, in the writer's opinion, is that it fails to explain the occurrence, emphasized by Wells,[33] of pillow structure and other signs of submarine extrusion in many normal basalts as well as in the spilites. Correns[34] has reported a normal labradorite basalt from a depth of 2,000 meters in the Atlantic Ocean. The conditions of submarine eruption, therefore, do not necessarily bring about albitization. Furthermore, if Backlund is correct,[35] some spilites are of subaerial origin. The theory also does not account for intrusive albite diabases except by appealing to an auxiliary hypothesis such as assimilation of wet sediments. Nor does it adequately account for the association of keratophyres and spilites, for no reason is advanced why the trondhjemitic type of differentiation, to which is attributed the derivation of most keratophyres from normal basaltic magma, should be found in especially frequent association with the similarly albitic spilites. Their common association must, as emphasized especially by Wells and Dewey and Flett, be referred to a common magmatic influence.

---

[32] Beskow, G.: op. cit., pp. 287-289.
[33] Wells, A. K.: op. cit., pp. 66, 73, 1923.

It appears that the suggestion of Daly[36] that the abundant soda of the spilites has been concentrated from an underlying mass of basaltic magma through the action of resurgent water, in conjunction with Goldschmidt's outline of trondhjemitic differentiation,[37] satisfactorily accounts for most of the features of the spilitic rocks. Daly emphasizes the testimony of the quartz diabase sills of Ontario studied by Bowen[38] and Collins[39] as to the production of albitic differentiates. These sills intrude argillites and have salic segregations of quartz and albite toward the roof with albite-rich veins and dikes and adinoles in the roof testifying to soda-rich phases in the consolidation of the rocks, although the diabases are as a whole normal or with only a little quartz and micropegmatite. Bowen suggested that the water originally contained in the sediments took an important part in the transfer of the albite from the normal basaltic magma. Daly points out the fact that the submarine locus of the spilites implies their eruption through thick masses of wet sediments. "Under these conditions water-gas must play an important rôle in modifying the magma in the vents and it seems impossible to doubt that occasionally the upper part of the magma column and also some of the extruded lava will become albitized." The testimony of the commonly fragmental keratophyres and quartz keratophyres associated with the spilities, clearly indicating explosive eruptions and the probability of intensive hydrothermal action in the volcanic vents, must be regarded as strong support for this conception.

---

[34] Correns, C. W.: Chemie der Erde, Bd. 5, s. 76, 1930, cited by Backlund.

[35] Backlund, H. G.: op. cit., pp. 36-40, 57.

[36] Daly, R. A.: Igneous rocks and their origin: pp. 339-340, New York, 1914.

[37] Goldschmidt, V. M.: op. cit., 1922.

[38] Bowen, N. L.: Diabase and granophyre of the Gowganda Lake district, Ont.: Jour. Geol., vol. 18, pp. 658-674, 1910.

[39] Collins, W. H.: The quartz diabases of Nipissing district, Ont.: Econ. Geol., vol. 5, pp. 538-550, 1910.

The large volume of keratophyres and quartz keratophyres (in eastern Oregon and many other localities far exceeding that of the spilites) suggest, however, that some differentiation at depth is needed to account for these siliceous rocks. Much of their quartz is apparently of intra-telluric origin, judging by the rounded forms and rhombic cleavage of the phenocrysts, and the occurrence of glassy rocks with phenocrysts of oligoclase and quartz indicates the igneous origin of these lavas. They are the effusive equivalents of trondhjemitic magma. The occurrence of these rocks in association with wet sediments conforms to Goldschmidt's thesis as to the effect of assimilated water (which his theory derived from the wall rocks of the intrusion but which might quite as well be absorbed by bulk engulfment of wet sediments) in producing, through early crystallization of biotite, a relative improverishment of the residual magma in K_2O and Al_2O_3. This results in albitic feldspars not only at the expense of orthoclase but also because the Al_2O_3 may be insufficient to satisfy the CaO for anorthite. At the same time the water constantly acts to lower the temperature of consolidation so that albite is relatively more stable and anorthite less stable, the more hydrous the magma. Thus the same environmental conditions which would, according to Daly, favor the presence of resurgent water carrying albite in solution, would also favor, by assimilation and differentiation at depth, the evolution of trondhjemitic magma which might be ejected as quartz keratophyre effusives. The residual solutions given off as the end stage of this type of differentiation would be expected to be highly albitic. Their former presence may be attested not only by albitization of the effusive rocks but also by the albite granites commonly associated with the spilitic rocks which in eastern Oregon at least are thought to be of metasomatic origin. The albitic solutions so widely prevalent in the rocks may thus have been in part of resurgent origin as in Daly's theory, but they were probably in large part of deep-seated derivation.

If this trondhjemitic type of differentiation be pictured as typical of geosynclinal intrusions (though obviously not necessarily limited to the geosynclinal environment) a source of hydrous soda-rich solutions seems readily available either to enrich a basaltic magma in soda or to albitize an earlier flow or intrusion by contact metasomatism. The common hydrothermal (post-magmatic) replacement of potash feldspar by albite, like that so well known from pegmatites, may be responsible in part for the low K_2O shown by most spilites and albite diabases relative to other basaltic rocks. Partial albitization of some flows and sills, the occurrence of albitized flows in the midst of un-albitized, and similar irregularities in distribution become more readily reconciled with this hypothesis than with any of the others known to the writer, for such apparent caprice is familiar to every worker in igneous metamorphism.

We have here a possible explanation of the otherwise anomalous sequence described by Beskow from Swedish Lappland and occurring also in eastern Oregon, namely, the sequence from albitic volcanics to normal intrusives followed by albitic intrusives—the intrusives separated from the earlier volcanics by an orogenic period. The conclusion to be drawn from this appears to be that the influence of the tectonic conditions (supposedly slow subsidence) in geosynclines is not the determining factor in the evolution of spilitic rocks. Rather this evolution seems to be controlled by availability of water to the magma. The submarine locus is naturally favorable to this in shallow intrusions and extrusions; water-rich wall rocks favor it in deeper-seated intrusions. If this factor is determining, it is thus quite to be expected that geosynclines should be favored places for spilitic and keratophyric volcanic rocks and for trondhjemitic intrusives. But through local anomalies a similar differentiation trend may proceed under other environmental conditions—thus, for example, accounting for the keratophyres of Tonopah, Nevada, where, apparently, no geosynclinal sediments nor submarine origin can be appealed to as factors in their development.

ANALYSES USED IN FELDSPAR DIAGRAM.

Albite diabases.

Locality	*Analyst*	*Reference*
1. Trusham Station, Devon	E. G. Radley	Flett, J. S.: Geology of Newton Abbot, p. 62.
2. N. E. of Ardifuar, Argyll	E. G. Radley	Flett, J. S.: Geology of the seaboard of Mid. Argyll, Mem. Geol. Survey Scotland, p. 55.
3. Ardifuar, Argyll	E. G. Radley	Flett, J. S.: idem.
4. Newlyn, Cornwall	J. A. Phillips	Flett, J. S.: Geology of the Land's End district, Mem. Geol. Survey of England, p. 35.
5. Newlyn, Cornwall	W. Pollard	Flett, J. S.: idem.
6. Piz Mondin, Switzerland	L. Hezner	Grubenmann, U.: Beitr. zur Geologie des Unterengadins, Beitr. zur Geol. Karte der schweiz, No. 23, p. 236, 1909.
7. Mönchs, Harz	Rudeloff	Lossen, K. A.: cited by Pelikan, A., Die Schalsteine des Fichtelgebirges etc., Sitzb. K.k. Akad. Wien, Bd. 108, pt. 1, p. 776, 1899.
8. Magdesprung, Harz	Carmichael	Lossen, K. A.: cited by Pelikan, idem.
9. Hartenrod, Hesse	F. Heineck	Heineck, Fr.: Die Diabase an der Bahnstrecke Hartenrod-Ubernthal bei Herborn, Neues Jahrb. Beil. Bd. 17, p. 110, 1903.
10. Hartenrod, Hesse	F. Heineck	Idem: p. 98.
11. Tarasp, Switzerland	L. Hezner	Grubenmann, U.: op. cit. p. 237.
12. Alp Champatsch, Switzerland	L. Hezner	———: op. cit. p. 234.
13. Alp Champatsch, Switzerland	L. Hezner	———: op. cit. p. 238.
14. Pazza below Remus, Switzerland	L. Hezner	———: op. cit. p. 235.
15. Valkeasiipiraara, Kiruna, Sweden	N. Sahlbom	Sundius, N.: Geologie des Kirunagebiets, Vetensk. och Prakt. Unders. in Lappland, Uppsala, p. 63, 1915.
16. Piz Tomül, Switzerland	H. Roothan	Roothan, H.: Petrographische Untersuchungen in der Bergen der Umgebung von Vals; Jahresb. der Naturforsch. Gesell. Graubündens, Neue Folge. Bd. 59, p. 117, 1918.
17. Kuusniemi, Aunus, U.S.S.R.	P. Eskola	Eskola, P.: The mineral development of the basic rocks in the Karelian formations, Fennia, vol. 45, p. 33, 1925.
18. Perttilahenvaara, Aunus, U.S.S.R.	P. Eskola	Idem, p. 39.
19. Nundle, New South Wales	W. N. Benson	Benson, W. N.: The geology and petrology of the great serpentine belt of New South Wales: Proc. Linnean Soc. N.S.W., vol. 38, p. 704, 1913.

Locality	*Analyst*	*Reference*
20. S. W. of Bingara, New South Wales	W. N. Benson	Benson, W. N.: idem. p. 704.
21. Bowling Alley Point, New South Wales	W. N. Benson	Benson, W. N.: idem. vol. 40, p. 139, 1915.
22. Nemingha, New South Wales	W. N. Benson	———: vol. 40, p. 602.
23. Bowling Alley Point, N. S. W.	W. N. Benson	———: vol. 40, p. 139.
24. Munro's Creek, New South Wales	W. N. Benson	———: vol. 40, p. 139.
25. Kittilä, Finland	L. Lokka	Hackman, V.: Studien über den Gesteinsaufbau der Kittilä-Lappmark, Comm. Geol. Finland, Bull. 79, p. 21, 1927.
26. Holkkuavaara, Kittilä-Lapmark, Finland	L. Lokka	Hackman, V.: op. cit. p. 22.
27. Holkkuavaara, Kittilä-Lapmark, Finland	L. Lokka	———: op. cit. p. 22.
28. Levijoki valley, Kittilä-Lapmark, Finland	L. Lokka	———: p. 23.
29. Poorman mine, Pine quad., Oreg.	J. G. Fairchild	This paper, Table 1.
30. N. of Lendalfoot, S. Ayrshire	B. E. Dixon	Balsillie, D.: The Ballantrae igneous complex, S. Ayrshire: Geol. Mag. vol. 69, p. 126, 1932.
31. S. of Lendalfoot, S. Ayrshire	B. E. Dixon	———: etc.

Spilites.

Locality	*Analyst*	*Reference*
1. Crystal Falls, Mich.	H. N. Stokes	Clements, J. M.: The Crystal Falls iron-bearing district, Michigan: U. S. G. S. Monograph 36, p. 106, 1899.
2. Crystal Falls, Mich.	H. N. Stokes	———: p. 106.
3. Crystal Falls, Mich.	H. N. Stokes	———: p. 106.
4. Pt. Bonita, Calif.	F. L. Ransome	Ransome, F. L.: The eruptive rocks of Point Bonita: Univ. Calif. Bull. Dept. Geol. vol. 1, p. 106, 1893.
5. Amlwch, Anglesey	J. O. Hughes	Greenly, E.: Geology of Anglesey: Mem. Geol. Surv. England & Wales, p. 55, 1919.
6. Tregidden, Cornwall	E. G. Radley	Flett, J. S., and Hill, J. B.: Geol. of the Lizard and Meneage: Mem. Geol. Surv. Gt. Britain, p. 185, 1912.
7. Mullion Island, Cornwall	W. Pollard	Flett, J. S., and Hill, J. B.: idem.
8. Port Isaac, Cornwall	J. A. Phillips	Flett, J. S.: in Geol. of Plymouth and Liskeard: Mem. Geol. Surv. Gt. Britain, p. 47, 1907.
9. Pentire Point, Cornwall	J. A. Phillips	Flett, J. S.: idem.

Locality	*Analyst*	*Reference*
10. Bickington, Devon	E. G. Radley	Flett, J. S.: Geology of Newton Abbot: Mem. Geol. Surv. Gt. Britain, p. 56, 1913.
11. Devonport Workhouse, Devon	E. G. Radley	Flett, J. S.: Geol. of Plymouth and Liskeard, p. 97.
12. Dduallt, Merioneth	H. F. Harwood	Wells, A. K.: The geology of the Rhobell Fawr district, Merioneth, Geol. Soc. London Quart. Jour. vol. 81, p. 512, 1925.
13. Kilbride, Ireland	J. Weintraube	Gardiner, C. I., and Reynolds, S. H.: The Ordovician and Silurian rocks of the Kilbride Peninsula, Mayo. Geol. Soc. London Quart. Jour. vol. 68, p. 96, 1912.
14. Newborough Dunes, Anglesey	J. O. Hughes	Greenly, E.: op. cit. p. 74.
15. Gatelochside Burn, Scotland	J. J. H. Teall	Teall, J. J. H.: The Silurian rocks of Great Britain, vol. 1, p. 85, 1899.
16. Tayvallich, Scotland	E. G. Radley	Flett, J. S.: The geology of Knapdale, Jura and Kintyre: Mem. Geol. Surv. Gt. Britain, p. 87, 1911.
17. Mine Barre, Czechoslovakia	V. Vesely	Slavik, F.: Les "pillow-lavas," Algonkiennes de la Bohême: Extrait des Comptes-Rendus, 14th Congrès Géol. International, p. 7, 1929.
18. Vodochody, Czechoslovakia	V. Vesely	Slavik, F.: idem.
19. Lökken mine, Norway	O. Röer	Goldschmidt, V. M.: Ubersicht der Eruptivgesteine im kaledonischen Gebirge zwischen Stavanger and Trondhjem: Vidensk Skrift. Mat. Nat. Klasse I, p. 15, 1916.
20. Hage bro, Norway	O. Röer	Goldschmidt, V. M.: idem.
21. Dragset mine, Norway	N. Sahlbom	Carstens, C. W.: Der unterordovicische Vulkanhorizont in dem Trondhjemgebiet: Norsk. Geol. Tidsk. Bd. 7, p. 202, 1924.
22. Frilsjöen, Lokken, Norway	N. Sahlbom	Idem, p. 195.
23. Skjödskrift, Norway	N. Sahlbom	Carstens, C. W.: idem, p. 202.
24. Pahtosvaara, Kiruna district, Sweden	G. Nyblom	Sundius, N.: op. cit. p. 63.
25. Hills N. of R.R. Kiruna, Sweden	N. Sahlbom	Sundius, N.: op. cit. p. 63.
26. Below the "Horn," Vals, Switzerland	H. Roothan	Roothan, H.: op. cit. p. 133.
27. Oberstafel, Vals, Switzerland	H. Roothan	———: p. 131.
27a. Piz Tomül, Vals, Switzerland	H. Roothan	———: p. 121.
28. Piz Tomül, Vals, Switzerland	H. Roothan	———: p. 119.
29. Ardez, Switzerland	L. Hezner	Grubenmann, U.: op. cit. p. 243.
30. Aschera, Switzerland	L. Hezner	———: op. cit. p. 240.

	Locality	Analyst	Reference
31.	Ardez, Switzerland	M. Dittrich	Grubenmann, U.: op. cit. p. 240.
32.	Tandjoung Nousaniwi, Ambon	J. S. von Winarski	Verbeek, R. D. M.: Description géologique de l'île d'Ambon, Jaarb. van het Mijnwezen in Nederl. Oost Ind. Batavia vol. 34, p. 246, 1905.
33.	Leitimor, Dutch East Indies	T. Döring	Verbeek, R. D. M.: idem.
34.	Leitimor, Dutch East Indies	F. Jaronski	———: idem.
35.	Kulmuksa, Aunus, U.S.S.R.	P. Eskola	Eskola, P.: op. cit. p. 24.
36.	Kendjärvi, Aunus, U.S.S.R.	P. Eskola	———: op. cit., p. 19.
37.	Solomen, Lake Onega, U.S.S.R.	P. Eskola	———: op. cit., p. 13.
38.	Nundle, New South Wales	W. N. Benson	Benson, W. N:. op. cit., vol. 38, p. 704.
39.	Nemingha, New South Wales	W. N. Benson	———: op. cit., vol. 40, p. 602.
40.	Bowling Alley Point, New South Wales	W. N. Benson	———: op. cit., vol. 40, p. 139.
41.	Sotkajärvi, Kittilä, Finland	L. Lokka	Hackman, V.: op. cit., p. 18.
42.	Valkeasiipivaara, Kiruna, Sweden	A. Bygden	Sundius, N.: On the Spilitic rocks, Geol. Mag. vol. 67, p. 6, 1930.
43.	Sulitelma, Norway	N. Busvold	Vogt, Th.: Sulitelmafältets geologi och petrogrefi, Norsk. Geol. Under. No. 121, p. 243, 1927.
44.	Keating district, Oregon	J. G. Fairchild	This paper, Table 1.

U. S. Geological Survey,
Washington, D. C.

ARKOSE DEPOSITS IN THE HUMID TROPICS. A STUDY OF SEDIMENTATION IN SOUTHERN MEXICO.

PAUL D. KRYNINE.

INTRODUCTION.

The predominance of chemical decomposition over mechanical disintegration in the humid tropics has been accepted for a long time as an established fact. The possibility that this is far from being always the case does not seem to have been sufficiently recognized. As a matter of fact, under certain circumstances, mechanical disintegration may entirely overshadow chemical decay. The prerequisite for this condition is an extremely heavy seasonal rainfall in a region of rugged topography. In such cases erosion assumes an extraordinary vigor and some of the resulting geomorphic and sedimentary features are strangely similar to those produced in a semi-arid region.

This is less paradoxical than it appears to be at first sight if the fundamental processes at work in both cases are compared. Violent cloudbursts separated by long periods of dryness are characteristic of a semi-arid or an arid climate. Under such conditions, erosion will be the result of the sudden and violent application of relatively large volumes of water to slopes poorly protected by vegetation.

However, similar results will be obtained if, in an extremely humid climate, the seasonal rainfall in a mountainous region assumes periodically an intensity sufficient to break through and sweep away the vegetation cover. Extremely powerful erosive processes immediately develop on the now unprotected slopes and mechanical disintegration, as described below, takes precedence over chemical decay. The resulting débris are carried away so swiftly and covered up so rapidly upon deposition that their freshness is hardly impaired.

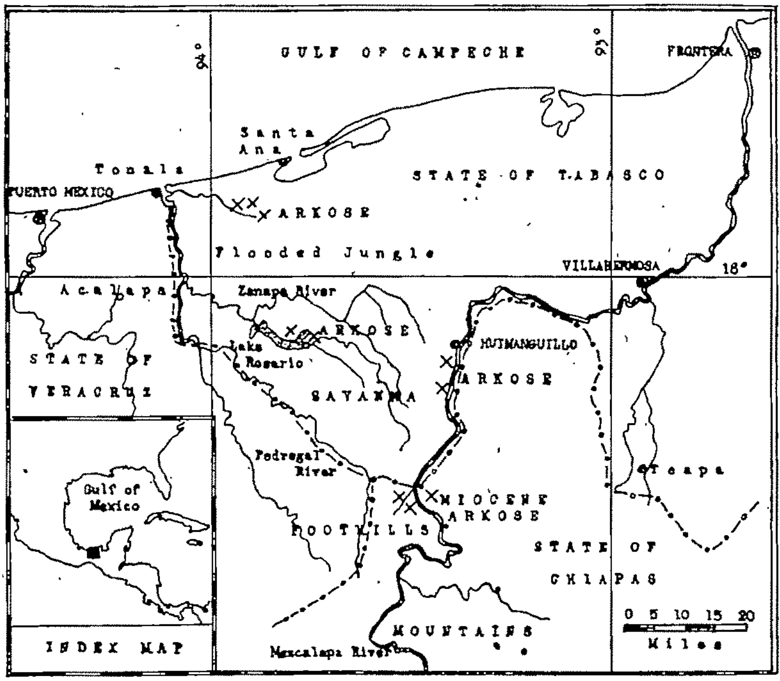
Such processes are at work in the western part of the state of Tabasco, southern Mexico, and as a result, arkose deposits of surprising freshness are being formed in a climate which, according to accepted ideas, should be characterized by deeply weathered and decomposed sediments.

Other features commonly associated with a semi-arid climate such as mud-cracks, rill-marks, footprints, eolian sands, and incipient alluvial fans have also been discovered in this region.

The writer is indebted to Mr. G. C. Gester, Chief Geologist of the Standard Oil Company of California for permission to publish the result of geological observations made while in the employ of the Company in 1929-1930, and to Professors Dunbar, Flint, and Knopf of Yale University for helpful suggestions and criticism.

GEOGRAPHY AND CLIMATE.

The region under discussion lies along the coast of the Gulf of Campeche, the southernmost part of the Gulf of Mexico. It comprises the western part of the state of Tabasco and small adjoining parts of the States of Vera Cruz and Chiapas, Mexico.



The climate is tropical with an exceedingly heavy rainfall. The mean annual temperature is 80° F. (25°-26° C.). The rainfall differs in the four geomorphic provinces of the region. On the coast it fluctuates between 100 and 120 inches, and in the mountains it reaches 250 and even 300 inches per year. Meteorological data, from a few typical localities are given below.

Meteorological Data.

Province	Locality	Latitude	Elevation	Mean Yearly Temp.	Temp. Coldest Month	Annual Rainfall	Dry* Season Rainfall	Climatic Formula†	Lateritic Index‡
Coastal Plain	Puerto Mexico	18° 09′	14 m.	25° C.	21.3° C.	2914 mm.	151 mm.	Amw″	75.7
Savanna Belt	Villahermosa	17° 59′	20 m.	.....	.....	2012 mm.	.....	.....	...
Savanna Belt	Huimanguillo	17° 51′	15 m.	.....	.....	1749 mm.	.....	.....	...
Foothill Zone	Teapa	17° 33′	45 m.	25.2° C.	21.5° C.	4095 mm.	366 mm.	Afw″	87.0
Foothill Zone	Tenosique§	17° 29′	60 m.	27.6° C.	23.9° C.	2217 mm.	79 mm.	Amw″	71.7
Mountain Front	La Primavera§	17° 23′	800 m.	.....	.....	5741 mm.	.....	.....	...

* Three months.

§ Not on map.

† After Köppen's classification (7).

‡ Computation after Kerner von Marilaun's formula (3).

There is a marked dry season in April and May, when there is no rainfall whatever. Occasional storms take place in March, June, July and August. The heavy rains are concentrated between September and February.

GEOLOGY AND GEOMORPHOLOGY.

Regional Description.—Geologically the region belongs to Central rather than North America. Deposition was active in Tertiary time and over 12,000 feet of sedimentary rocks were formed during that period. They are mostly sandstones and shales with subordinate limestones and locally thick and well-indurated conglomerates. Feldspathic and micaceous material is abundant throughout the series. Some of the Miocene horizons can be definitely classed as arkoses.

The topography of the region reflects the two major structural movements which have taken place since the end of the Pliocene period. The main post-Pliocene orogenesis created the mountain front and the foothills and shaped the broad geomorphic features of the country.

After erosion in the southern mountains and deposition in the northern plains had been in progress, a rotational tilting movement elevated the eastern part of the basin of deposition and subjected it to renewed erosion. At the same time the western part of the basin was depressed and here sedimentation kept on progressing.

As a result we have in the northern and northwestern parts of the region, first, a swampy alluvial plain, and then, further inland, a flat savanna. Both are covered with a thick mantle of Pleistocene and Recent alluvium. In the central and southeastern parts, this alluvial mantle is being subjected to erosion and forms a hilly topography of moderate relief. Further south, the country consists of rugged hills made of Tertiary rocks which gradually pass into the high mountains of the Sierra Central de Chiapas. In accordance with this, the area can be divided into the four geomorphic provinces described below (Fig. 1).

The Low Coastal Plain.—The shoreline of western Tabasco is essentially a shoreline of emergence, partly modified by later submergence. Between Tonalá and Santa Ana a line of sand dunes skirts the straight and monotonous sandy beach and extending for a distance of two to four kilometers inland it rises to elevations up to 50 feet. As a result of coastal emergence the dune belt has been gradually widened and the older dunes, once left behind, have been immediately seized and fixated by a luxuriant vegetation. As the water table is permanently very high, the dunes support a heavy jungle growth and the top soil layer consists at the present time of a black organic matter several feet thick. It was necessary to dig a series of pits in order to discover the character and extent of the real substratum, which proved to be eolian sand. These dunes can hardly be identified from the surface except by their lack of a systematic drainage pattern.

Reed marshes flank the jungle-covered sand dune belt. The jungle again gains a footing on the higher ground formed as natural levees along the margins of inland streams and arroyos which drain these swamps. To the south the marshes give way to large areas of jungle covered flats—the real mainland. The monotony of the northern part of the coastal plain is interrupted by a few isolated low hills which appear as remnants of an older topography buried by the recent alluvium. One of the arkose deposits described below is located in this region.

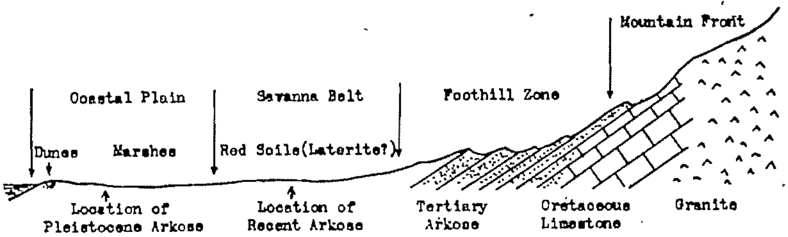


Fig. 1. Generalized North-South Section passing through Santa Ana.

The Savanna Belt.—A slight elevation of the coastal plain in the region south of the Zanapa River introduces the savanna jungle belt of gently undulating plains which reach a maximum elevation of about 100 feet south of Lake Rosario. Conditions of extreme aridity prevail here during the two or three months of the dry season. The water table sinks during this period and this prevents the development of a thick jungle. Instead, we have a xerophilous vegetation of grass and low shrubs with a few drought resistant trees. Extending in long fingers along streams and lakes, however, a luxuriant vegetation of the forest type is found.

Due to the considerable variations of the ground water table, atmospheric solutions can easily penetrate downward and deep oxidation takes place, for there is a deficiency in organic material. As a result red soils are formed, especially in the uplands. The appearance of these soils in many cases is lateritic, but the absence of chemical analysis prevents any definite statement on this subject. However, the "lateritic Index" for the region, computed after Kerner von Marilaun's (3) formula, was found to range between 70 and 80 as compared with 67.1 for Bombay, a typical laterite country. Hence, it is not unreasonable to suspect that some of these red soils are true laterites. According to Blanck and Harrassowitz (2) the region is lateritic.

The Foothills, or Cuesta Province.—A line of low hills running north of the Pedregal and west of the Mezcalapa River with cliffs of Pleistocene and Recent sands and sandstones over 60 feet high forms the transitional zone between the savanna belt and the foothills. The latter flank the depressed area of the coastal plain in a curving zone of roughly parallel strike ridges and minor relief due to folding and uplift. Elevation of the ridges reaches 1000 feet above sea level and 500 feet above the canyon floor. Crest lines of ridges are very regular and of even height. Rainfall is much heavier here than on the coastal plain. Erosion therefore proceeds rapidly, largely by undermining and headwater erosion. The entire area is heavily forested.

The Mountain Front.—The change from the foothills to the high mountain front is gradual. Hills become higher, their maximum elevation reaching 5000 feet. All this country is also covered by a dense tropical jungle. The rainfall is extraordinarily heavy: 300 inches per year.

ARKOSE DEPOSITS.

Two major arkose deposits of Recent date were observed in the region. The first was found in the marshy part of the lower coastal plain between Tonalá and Santa Ana. This particular region has a rainfall exceeding 120 inches per year and the average elevation of the district is 2 feet above mean tide. The deposit is related to a so-called "hill," i.e., a topographic feature standing from 5 to 40 feet above swamp level and covering an area of 4 to 5 square miles. The arkose was seen in no less than 18 pits well distributed over the entire surface of the "hill." The pits were excavated until they cut the ground water table and further progress became impossible. Their depth was from 9 to 38 feet, according to the topography.

The arkose consists of medium-grained (½ mm.) subangular fragments of orthoclase (or microcline?), plagioclase, and somewhat larger pieces of quartz. The feldspars commonly appear to be quite fresh under the hand lens. In three instances the fragments are large enough to be designated as gravel (5 mm.) and to show distinct albite and Carlsbad twinning. Fragments of hornblende were found at one locality.* Feldspathic material was present in every pit and in 9 cases feldspar predominated to such an extent that the sand deserved to be called arkose outright. The color of the sand was red in 5 cases, yellow in 8, and white, grayish or pale greenish in 9, some of the pits showing banding, and exhibiting several colors. In only two instances was the sand indurated. A rude stratification and evidence of cross bedding were observed in 3 pits. This deposit was probably formed in late Pleistocene or early Recent times before the beginning of the present epoch of silt deposition on the lower coastal plain.

A second arkose deposit, now in the process of formation, was observed in the savanna belt, on the shore of Lake Rosario. Here, a beach of pure white arkosic sand, with many good orthoclase (or microcline?) crystals is present near the eastern end of the lake, and the same sand can be followed along the shore for a distance of 7 or 8 kilometers toward the middle of the lake. This arkosic beach sand is probably due to the sorting and reworking of the feldspathic gravel brought from the foothills into the lake.

Isolated occurences of feldspathic or arkosic material were furthermore repeatedly observed in pits dug in the transitional zone between the savanna and the foothills, especially in the region south of Huimanguillo. All the intermittent stream channels of the savanna are also covered with a thick coarse gravel containing abundant fragments of feldspar.

ORIGIN OF THE ARKOSE.

Source Rocks.—The original, primary source of the arkosic material now being deposited on the Coastal Plain of Tabasco must be sought among the granitic and gneissic terranes of the

---

* The accepted textbook view (Lahee (4), p. 36; Marr (6), p. 65) is that the presence of hornblende is typical of arid or glacial conditions.

Sierra Central de Chiapas. These terranes were subjected to erosion during Tertiary time and the resulting feldspathic and micaceous sediments form a thick series of Tertiary sandstones and sandy shales, part of which, especially that in the Miocene, deserve to be called arkose.

These Tertiary arkoses which underlie the foothills and mountains of southwestern Tabasco and northwestern Chiapas are being, in their turn, eroded. They provide the immediate source of the arkose deposits described above. The débris resulting from the erosion of Tertiary rocks is being carried into the savanna belt, and where conditions are favorable, arkose deposits are being formed from this reworked Tertiary material. In other words, in southern Mexico, feldspars are able to survive a double cycle of erosion and deposition under extremely unfavorable climatic conditions.

Formative Processes.—The prerequisites for the formation of arkose, as expounded by Barton (1), are, first, disintegration of the granitic rock with but slight accompanying decomposition, and, second, erosion and deposition of the débris with merely slight loss of feldspar.

Under the usual conditions of a humid tropical climate, chemical decomposition will greatly predominate over mechanical weathering. Also, a thick cover of vegetation will prevent rapid erosion and the survival of feldspars under such circumstances will appear to be impossible. However, if the rainfall becomes exceedingly heavy and is furthermore concentrated by a hilly topography, a condition may arise in which the volume of water supplied by an exceptionally intense cloudburst will be such that not even the dense vegetation of the tropics will be able to resist it.

Such conditions are not uncommonly present in the forested foothills and lower mountains of Tabasco and Chiapas. The rainfall in this region is around 200 inches or more per year or even per rainy season. Local breaks in the vegetation cover have been repeatedly observed after particularly heavy cloudbursts. The soil cover was then instantaneously swept away and the fresh bedrock was denuded, attacked, loosened, and removed almost immediately. The swiftness, violence, and completeness of the process are difficult to visualize unless actually seen. Canyons grow literally overnight by headward erosion and farther downstream, undermining is equally prominent. Woolnough (8) has described similar occurrences in the South Sea Islands.

The freshly eroded débris is contributed by the mountain streams to the main rivers which carry it rapidly away. The current of the Mezcalapa River has a velocity of over 5 miles per hour where it reaches the Tabasco-Chiapas boundary. An enormous amount of waste, including very large boulders, is thus easily transported downstream. Also the Mezcalapa River does a considerable amount of erosion during floods. In one instance lateral erosion cut 60 feet deep into a band of semi-consolidated Pleistocene sediments within 10 hours. In another place the same river gnawed away several feet of a very resistant Tertiary feldspathic sandstone bank during two months of rather moderate rains.

Thus, a very large quantity of freshly eroded, coarse débris is brought from the foothills into the savanna belt and deposited there, the lower strata being covered up very rapidly. At the same time the flattish interstream areas will be subjected to a long period of chemical decay. Deeply weathered residual soils and even possibly laterites will form on these uplands. The resulting close association of very fresh and completely decayed material is shown on the sketch below (Fig. 2). The possibility of such a close relationship between "arid" and "humid" deposits has been recently pointed out by Zeuner (9). Each deposit will give a true picture of the conditions prevailing at its source. In this case, however, the controlling factor will not be difference in climate, but only in relief.

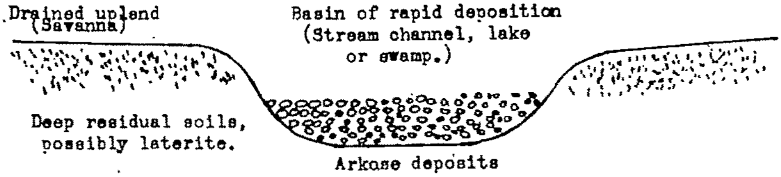

Drained upland (Savanna)
Basin of rapid deposition (Stream channel, lake or swamp.)
Deep residual soils, possibly laterite.
Arkose deposits

Fig. 2

DEVELOPMENT OF SEMI-ARID FEATURES IN THE HUMID TROPICS.

The dry season in western Tabasco, with its total absence of rainfall, provides many features usually associated with a semi-arid climate. During this period the majestic Mezcalapa

River, often several miles wide in flood time, shrinks to an insignificant stream. On the flood plain thus developed, mud-cracks and rill-marks appear almost immediately. The chances for such features of subaerial exposure to be incorporated in the fossil record, however, are not particularly good, for they will be attacked by bottom currents during the next high-water period. Nevertheless, the fact remains that these features are formed under humid tropical conditions, and to a minor degree they probably can be preserved. A paper dealing with the possibility of such a preservation is to be published shortly by Jüngst, in the Geologische Rundschau.

No typical fanglomerates have been found in the region, but small incipient fans have been repeatedly observed at the confluence of mountain streams. These fans, in many places, contain angular boulders up to 5 feet in diameter. The connection that is usually made between fanglomerates and an arid climate may possibly be due, to some extent, to the fact that in the vast majority of cases, fault scarps (an ideal localizing factor for the formation of fanglomerates) happen to be located geographically in desert regions. One wonders to what extent the small incipient fans of northern Chiapas would have grown if the parent localizing factor had been a major structural feature instead of the relatively insignificant break in the slope at the junction of mountain valleys. It is not entirely unreasonable to suppose that a large scarp in a humid tropical region with a seasonal rainfall and intermittent streams could easily lead to the formation of fanglomerates. That fanglomerates should not be considered a feature typical of semi-aridity has been recognized by Leuchs (5).

A fairly large mudflow was observed in a densely forested region near Acalapa during the rainy season. Apparently it was caused by the flowage of a very weak and porous shaly sandstone. The mudflow started in a small tributary valley, with a rather steep slope and a width of approximately 150 feet. After following the valley for possibly 750 feet, the flow debouched into the larger main valley and kept on flowing on the gentler slope of the latter for perhaps 500 feet farther.

The association of eolian dune sands with the lagoons and marshes of the coast has been pointed out already. This relationship is, of course, purely accidental, but is interesting as indicating how the association of apparently mutually excluding features may complicate paleoclimatic interpretation.

BIBLIOGRAPHY.

1. Barton, D. E.: "The Geological Significance and Genetic Classification of Arkose Deposits," Jour. Geol., 24, 417-449, 1916.
2. Harrassowitz, H.: "Böden der tropischen Regionen," in Blanck's "Handbuch der Bodenlehre," 3, 362-436, 1930.
3. Kerner von Marilaun: "Der klimatische Schwellenwert des vollständigen Lateritprofils," Sitz. Akad. Wiss. Wien; Math-nat. Kl., Abt. 11 a, 7, 413-428, 1927.
4. Lahee, F. H.: "Field Geology," 789 p., New York, 1931.
5. Leuchs, K.: "Uber Breccien," Geol. Rundschau, 24, 273-284, 1933.
6. Marr, J. E.: "Deposition of Sedimentary Rocks," 245 p., Cambridge, 1929.
7. Sapper, K.: "Klimakunde von Mittelamerika," in Köppen's "Handbuch der Klimatologie," 2 H, 74 p., 1932.
8. Woolnough, W. G.: "The Influence of Climate and Topography in the Formation and Distribution of Products of Weathering," Geol. Mag., 67, 123-131, 1930.
9. Zeuner, F.: "Die Schotteranalyse," Geol. Rundschau, 24, 65-104, 1933.

YALE UNIVERSITY,
NEW HAVEN, CONN.

STRIATED ROCK SURFACES IN THE ST. FRANCOIS RIVER VALLEY

CHESTER K. WENTWORTH.

Board of Water Supply, Honolulu, T. H.

In connection with search for striated cobbles in non-glacial areas[1] and the study of river ice work in the Yukon River basin,[2] the writer has examined closely the rock surfaces exposed in river channels in several regions. Certain markings may be regarded as quite normal to rock surfaces in stream channels but others, like those described below, appear to be the results of processes either no longer operative or so infrequently active that they are little known.

The headwaters and several branches of the St. Francois River in southeastern Missouri drain the central St. Francois mountain region where pre-Cambrian igneous rocks outcrop in a large number of separate areas. These are now marked by rounded knobs of granite or porphyritic felsite between which lie irregular basins floored by Cambrian sediments. The streams follow irregular courses and in places have cut short, narrow gorges in igneous rock, the result of superposition from a high-level erosion surface developed mainly if not exclusively on a Paleozoic cover over the igneous knobs. These short gorges, strikingly in contrast with the adjacent parts of the valleys cut in sedimentary rocks, are locally known as shutins. They are characterized by steep gradients and by rocky floors and walls, marked by much jointing. During low water much of the channel area is exposed to view and on these rock surfaces in several of the shutins the striations described below were found.

Three rather distinct types of surfaces need to be distinguished. The first of these is most general and is not striated. This consists of rounded knobs, tortuous potholed grooves and channels, and the like. It is obviously smoothed and rounded by the action of water and rock débris. The second type is best developed in some of the granite shutins where jointing parallel to the floor and walls of the gorge has apparently facilitated the formation of a smooth-floored,

---

[1] Wentworth, C. K.: Striated Cobbles in Southern States, Bull. Geol. Soc. Amer., Vol. 39, pp. 941-954, 1928.

[2] ————: The Geologic Work of Ice Jams in Subarctic Rivers, Washington Univ. Studies, Science and Technology Series, No. 7, pp. 47-80, 1932.

U-shaped channel or chute. Such surfaces in places are wavy in configuration, the form being much like the waves in a water body, each trough having a shallow concavity and separated from its neighbor by a cuspate ridge. The waves on some surfaces are not over 10 to 15 inches long and the crests rise scarcely a half inch above the troughs. Direction of movement of the water is indicated by the slight irregular scratching of the surface and by the fact that upstream cavities overlap and cut into those next downstream. Surfaces similar to this but on a small scale are sometimes developed by sand-blasting on hard, siliceous rocks, where each small concavity resembles a tooth mark in a gnawed surface. A surface of this kind is illustrated in Fig. 1.

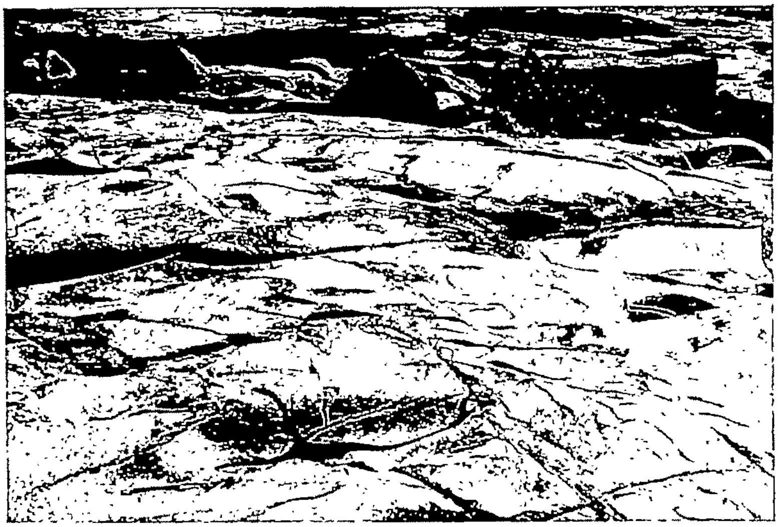


Fig. 1. Wavy, abraded rock surfaces cut in granite in the St. Francois River channel. The distance between crests is one to two feet. Stream flow is from left to right.

The third type of surface, the special subject of this paper, is found both on the smooth rock of the trough-shaped parts of some shutins, and also on the tops of a few high remnants of bedrock, or large blocks which lie in other channels. Two features are outstanding, the first of which is the drastically planed or moulded character of the surface along lines roughly parallel to the channel. The resemblance to the surfaces of roches moutonnées or glacially smoothed bedrock surfaces is striking. Where the rock surface is broken by joints, the widened cracks in places seem subsequent to the action that planed the surface but in others there seems to be a fairly clear plucking of the lee margins and a definite rounding of stoss margins. Many of these surfaces on projecting masses of rock dip slightly up stream and suggest movement up and over them.

The second feature of these surfaces is the striation, often faint as to details, partially weathered away, but still in the right light showing a strong parallelism and continuity of striae. In this latter respect these striae differ markedly from those on the wavy rock surfaces. Again, the resemblance of these striations to those on roches moutonnées of glacial origin, or to the similar features formed in the Yukon valley by the action of river ice is very suggestive.[3] Another noteworthy characteristic is the evidence of modern decay and destruction of these surfaces. At several localities the striated surface is largely destroyed by exfoliation of thin layers of rock and only minor remnants of the scratched surface remain. It does not appear that such markings are now being produced and one marvels (if they really do date from a time of more active ice work) that they have not been more completely removed by atmospheric and fluvial agencies.

In certain places they may have been covered until recently, but their preservation still remains somewhat of a mystery, as does the preservation of the most minute glacial carvings on limestone ledges just above low water on the south bank of the Missouri due north of St. Louis. It would more readily be supposed that a few years of washing by débris-laden streams at higher stages would remove these striae at either locality.

No effort has been made to make a complete list of localities where these striations have been found. The best one known is the shutin on the main St. Francois River upstream from Silver Mine and downstream from the crossing of Highway 70. Near the upper end of this granite shutin, rock surfaces of types two and three are found, along with the much more extensive type one. Type two appears to be due to concurrent fluvial abrasion, probably by means of sand and fine gravel. Several large areas of type three occur on the south side of the stream where nearly continuous striation patterns cover areas as large as 20 x 30 feet. Numerous smaller remnants also occur (Fig. 2).

---

[3] Wentworth, C. K.: The Geologic Work of Ice Jams in Subarctic Rivers, Washington University Studies, Science and Technology Series, No. 7, Figs. 2 and 4, 1932.

Smaller remnants of this type of surface have been seen at the so-called Catherine dam in the Little St. Francois channel north of Fredericktown and in the main St. Francois channel east of French Mills about 12 miles southwest of Fredericktown. Careful search will doubtless reveal many other such remnants, though they are not known to have been described heretofore.

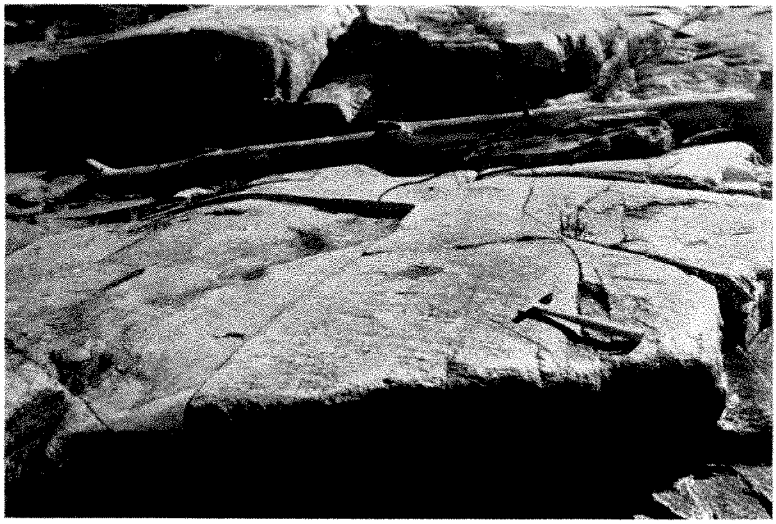


Fig. 2. Planed and striated rock surface in the St. Francois River channel. Parts of the original surface are removed by the spalling off of thin flakes and it does not appear to be formed by processes now active. Stream flow is from right to left.

The striated rock surfaces of type three have not been explained with complete satisfaction. Probably the most plausible interpretation is that they are the result of ice jams at a time when the climate was more rigorous and when the striated cobbles found in various other southern valley terraces were formed.[4] A few imperfect cobbles of this type have been found in the St. Francois valley, though terrace deposits in similar situation to those of the Tennessee and other valleys where such cobbles are abundant have not been found. That the rock striations are due to modern ice action is scarcely admissible, since ice is not known to form more than a few inches thick on the St. Francois and that very rarely. The possibility of timber jams producing the markings has been considered but seems remote. The extent and evident former general occurrence of these surfaces seem to call for an agent of more frequent and periodic activity than timber jams are likely to be. More extended observations and wider records of occurrence or non-occurrence of these surfaces seem essential to a final judgment as to their origin.

---

[4] Wentworth, C. K.: Striated Cobbles in Southern States, Bull. Geol. Soc. Amer., Vol. 39, pp. 949, 952, 953, 1928.

HONOLULU,
HAWAII.

THE ORIGIN OF THE POTASH-RICH ROCKS.

RUTH DOGGETT TERZAGHI.

ABSTRACT.

The term "orthoclase-rich" is applied to those rocks whose composition lies in the orthoclase field of the feldspar equilibrium diagram. Vogt has made the valuable suggestion that, toward the end of the crystallization process, when water is present in relatively large quantities in the liquid phase, potash and plagioclase feldspar may be in equilibrium with a liquid having a higher Or:Ab + An ratio than if the melt is "dry." Furthermore, high pressure, independent of its effect on the water-content of the magma, may be expected to displace equilibrium in the same sense. It also seems probable that some of the potash-rich rocks which appear to be of igneous origin may have been produced by metasomatic processes, chiefly by the feldspathization of quartzite. Moreover, during the hydrothermal alteration and weathering of igneous rocks, the potash: soda ratio may undergo a considerable increase which is not always accompanied by easily diagnosed changes in the appearance of the rock.

INTRODUCTION.

Two significantly different equilibrium diagrams for the system Or: Ab: An have been presented. Vogt[1] has derived one, of which two variations are shown in Fig. 1, from a study of the sequence of crystallization in individual rocks. Harker[2] has presented a similar one. Bowen[3] has suggested, on the basis of theoretical considerations, that the diagram for this system may have a form similar to that bearing his name in Fig. 1. In a previous paper,[4] I have shown that, with the exception of some of the granites and a few related coarse-grained rocks, the composition of the igneous rocks in which feldspar is the chief constituent tends to approach a definite series of values which correspond approximately to the field boundary of Bowen's suggested equilibrium diagram. In other words, nearly all rocks that appear to be of igneous origin, except the granitic group, lie either in the plagioclase field or on the supposed field boundary. This fact is thought to be strong evidence in favor of Bowen's hypothetical diagram.

---

[1] Vogt, J. H. L.: "The Physical Chemistry of the Magmatic Differentiation of Igneous Rocks, Pt. II, Skrifter, Norske Videnskaps Akademi, No. 4, p. 59, and Pt. III, Oslo, 1926. 2nd Half, Skrifter, Norske Videnskaps Akademi, No. 3, p. 225, Oslo, 1930.

[2] Harker, Alfred: Natural History of Igneous Rocks, p. 250, 1909.

[3] Bowen, N. L.: The Evolution of the Igneous Rocks, p. 229, Princeton, 1928.

[4] Doggett, R. A.: "The Orthoclase-Plagioclase Equilibrium Diagram," Journal of Geology, Vol. XXXVII, pp. 712-716, 1929.

Now, as has frequently been pointed out by previous writers, a solution cannot under equilibrium conditions cross the field boundary of the system orthoclase: plagioclase if this boundary is of the cotectic type postulated by most investigators. Therefore, if the petrographer accepts, at least tentatively, the hypothesis that igneous rocks were derived from a single type, or from a few closely related types of parent magma approaching basalt in composition, he is faced with the necessity of devising a special explanation for the origin of those rocks whose composition lies within the orthoclase field of the feldspar equilibrium diagram. While this problem must be faced, irrespective of which of the two proposed types of equilibrium diagram proves to be most nearly correct, the following discussion was written largely with reference to those rocks, chiefly granites, whose composition lies within the orthoclase field of the general type of equilibrium diagram proposed by Bowen.

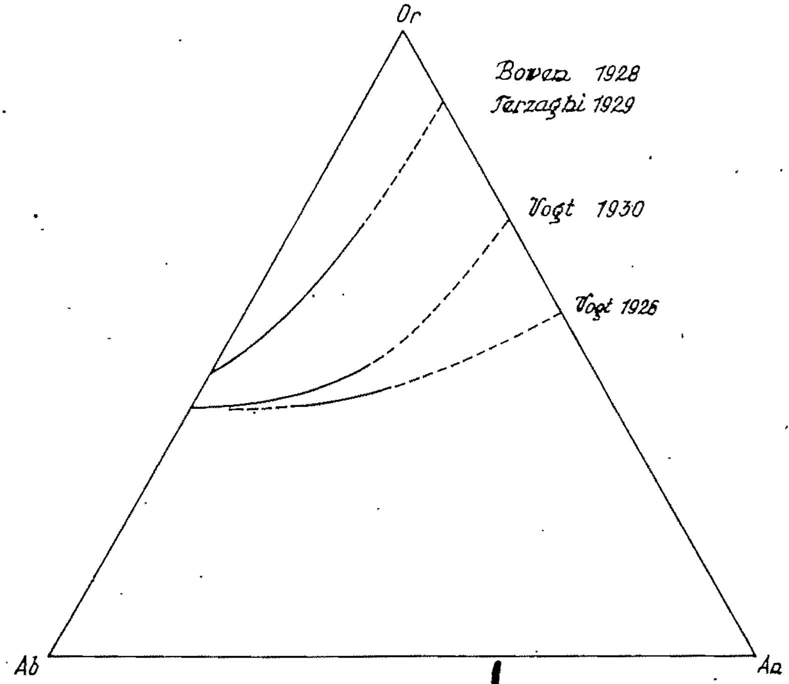


Fig. 1. Proposed equilibrium diagrams for the system Or : Ab : An.

This bias is not the result of an *a priori* discrimination, but of the fact that the most promising hypotheses for the origin of potash-rich rocks, which have been suggested or which have occurred to the writer, seem to apply particularly to the potash-soda rocks that lie in the orthoclase field of Bowen's diagram (as well as Vogt's), but not to the potash-soda-lime rocks which would also be "potash-rich" according to Vogt's diagram.

THE ORIGIN OF THE POTASH-RICH ROCKS OF TRUE IGNEOUS CHARACTER.

Bowen's Reaction Hypothesis. One way out of the difficulty has been suggested by Bowen[5] who postulates a reaction-relation between orthoclase and anorthite, rather than the eutectic relationship ordinarily assumed. Owing to this postulated reaction relation, solutions consisting largely of orthoclase and anorthite, with very little albite, could cross the field boundary, thus becoming potash-rich liquids. The liquids thus produced would probably have in general, a high anorthite: albite ratio, although further differentiation might produce small quantities of granitic liquid. For further discussion of Bowen's suggestion, the reader is referred to some of the reviews and articles[6] in which it has been taken up from various aspects.

This investigation throws a very important light on the subject of potash-rich rocks, and demonstrates conclusively what could only be suspected before, namely, that potash-rich rocks of normal "igneous" appearance, previously supposed to represent potash-rich magmas, may actually be the altered representatives of normal magmas. It may be that there are no potash-rich rocks among the products of primary crystallization and it is in any case certain that we have as yet no conclusive evidence for the existence of such rocks.

The Effect of Water on the Orthoclase: Plagioclase Ratio. In the concluding number of his series of articles[7] on the physical chemistry of the igneous rocks, Vogt has made a valuable contribution to the problem of the potash-rich rocks. In this paper, he presents frequency curves in which the percentage of Or in the total normative feldspar is plotted against the number of analyses corresponding to each of a series of values for the Or-percentage. These curves show that among the quartz porphyries, keratophyres, rhyolites, obsidians, comendites, pantellerites, granite aplites, and granites there are very striking maxima between 40% and 50% orthoclase in the total feldspar. In contrast to these groups are the granite pegmatities which show a maximum number of rocks containing about 62% orthoclase in the total feldspar. Vogt suggests that the high content of orthoclase in the pegmatites, and in some of the rocks of granitic composition may be due to a process of myrmekitization in which the last remaining liquid removes from the already crystallized material a certain amount of orthoclase, in whose place a sodic plagioclase is deposited. This potash-rich residual liquid may then be pressed out to crystallize elsewhere, either as potash-rich granite, or as pegmatite. The process of myrmekitization depends on a relatively high water-content in the magma, and hence on rather high pressure. Although Vogt does not express this process in general terms, the suggestion seems to be implicit in his article that equilbrium in feldspar-rich melts of the system Or: Ab: H_2O may be somewhat as represented in Fig. 2. While equilibrium in this system is, of course, a

---

[5] Bowen, N. L.: op. cit., Chap. XI.

[6] Larsen, E. S.: Review of "The Evolution of the Igneous Rocks," Ec. Geol., Vol. XXIV, pp. 448-451, 1929.

Vogt, J. H. L.: "The Physical Chemistry of the Igneous Rocks," Norske Vid. Ak. Skrifter, No. 3, pp. 238-239, Oslo, 1930.

Alling, H. L.: "The Position of the Cotectic Line between Potash Feldspar and Plagioclase and their Relations," this Journal, Vol. XXV, pp. 471-476, 1933.

[7] Vogt, J. H. L.: op. cit., pp. 23, 44-69, 90, 238-240.

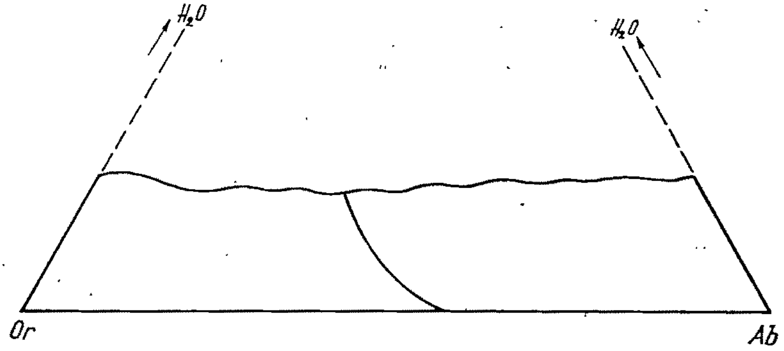


Fig. 2. Portion of hypothetical equilibrium diagram for the system Or: Ab: H_2O suggested by Vogt's discussion of the origin of the potash-rich rocks.

purely hypothetical matter, this implication of Vogt's myrmekitization hypothesis seems to be worth considering.

The Effect of Pressure on Equilibrium. Aside from the possible indirect effect of pressure on the ultimate composition of magma, owing to its influence on the amount of water present, pressure may exert directly an influence on the feldspar content because of the fact that the position of the cotectic line for the feldspar melt is a function of pressure. The present state of our knowledge of the feldspars unfortunately does not permit us to evaluate this effect of pressure on equilibrium with any certainty, owing to the difficulty of determining satisfactorily certain constants, particularly the latent heat of melting of orthoclase and albite, which refuse to crystallize as they cool from the liquid state in the laboratory. However, since the entire problem is shrouded in so much uncertainty, it may be worth while to point out that an increase of pressure of 1000 atmospheres might be expected to cause an increase of the order of magnitude of 6% of orthoclase in a liquid phase in equilibrium with both orthoclase and albite crystals, if the best available determinations of the latent heat of melting of orthoclase and of albite are approximately correct. (It must be remembered, however, that if the latent heats of melting of the minerals are approximately the same, as some investigators suspect, pressure would have very little effect on equilibrium between the two substances.) If pressure actually has the supposed effect on equilibrium, the boundary between the orthoclase and albite fields would, so to speak, be shifted into the orthoclase field. The boundary between the orthoclase and the anorthite fields would, on the other hand, be shifted into the anorthite field. For plagioclase of some intermediate composition, the orthoclase: plagioclase boundary would, therefore, not be affected by pressure.

That the "Terzaghi" field boundary shown in Fig. 1 represents equilibrium at low rather than at high pressure is indicated by the fact that it is based on the characters of fine-grained and glassy rocks, rather than on those of deep-seated origin, in all cases where there was a divergence between the two groups.

In order to estimate the difference between this low-pressure cotectic and one for a given higher pressure, we first calculate the effect of an increase of pressure on the melting points of the individual members of the system. In order to do so, we may avail ourselves of the well-known Clausius-Clapeyron equation[8]:

$$\frac{dP}{dT} = \frac{Q}{T\Delta v},$$

or, in the integrated form

$$\text{In}\ T_2 = \frac{\Delta v}{Qc}(P_2 - P_1) + \text{In}\ T_1,$$

where T_1 and T_2 are the melting temperatures of a given substance at pressures P_1 and P_2, respectively, Δv is the increase of volume attending the melting of one gram of the substance, Q the heat absorbed in calories upon melting of one gram, and c a conversion factor equal to 40.6 to be used when Q is expressed in calories and P in atmospheres. In order to make the discussion as concrete as possible with the limited data at our disposal, the increases in melting point for a change of pressure from one to one thousand atmospheres for orthoclase, albite, and anorthite are given in Table I. If we may assume a density of 2.7 for the outer shell of the earth, this pressure corresponds to a depth of about 3.7 kilometers. Owing to lack of exact data, it was necessary to make the following approximations which possibly introduce a certain amount of additional inaccuracy which, however, is negligible compared to the major uncertainty connected with the determination of the latent heats of melting of orthoclase and albite: Q, a

TABLE I.

Mineral	Δv	T (Abs.)	Q in cal./gram	calc Δ T/1000 Atm.
Orthoclase	0.034[9]	1443°[11]	109.4[12]	11°
Albite	0.036[10]	1373°[14]	48.5[13]	25°
Anorthite	0.0085[10]	1823°[14]	104.2[13]	4°

---

[8] The reader is referred to any good text-book of physical chemistry.

[9] Douglas, J. A.: Quart. Journ. Geol. Soc., vol. 63, p. 54, 1907, cited by C. Doelter, Handbuch der Mineralchemie, vol. I, p. 671, Steinkopf, 1912.

[10] Day and Allen: "The Isomorphism and Thermal Properties of the Feldspars," Carnegie Inst. of Washington, p. 74, 1905.

[11] Bowen, N. L.: op. cit., p. 229. The fact that orthoclase melts incongruently complicates matters, but for the present purpose it is assumed that there is sufficient quartz present to prevent incongruent melting.

[12] Boeke-Eitel, Grundlagen der physikalisch-chemischen Petrographie, 2nd Ed. p. 85, Borntraeger, Berlin, 1923.

[13] Bowen, N. L.: op. cit., p. 176.

[14] Bowen, N. L.: "The Melting Phenomena of the Plagioclase Feldspars," this Journal, vol. 35, p. 582, 1913.

function of temperature, is considered constant and equal to Q at the melting point corresponding to atmospheric pressure; for Δv, which varies slightly with temperature and pressure, the difference between the specific volume of glass and that of crystalline material at room temperature has been substituted. The data for the specific volume of anorthite glass may probably be considered satisfactory, since the relatively low viscosity of an anorthite melt permits the preparation of a glass which is free from vesicles, but whether the same may be said of the determinations of glasses of other feldspars is a matter of some doubt. The results of the various investigations which have been made on orthoclase and albite glasses vary considerably among themselves. Since the largest source of error is probably the presence of vesicles in the glass, which tends to give values too high for Δv, the smallest of the published determinations of this quantity was taken as being nearest to the truth. Even though later investigation may show that the data for Δv for orthoclase and albite given in Table I are too high, it is not likely that the *relation* of the calculated changes of melting point with pressure for the two minerals would be greatly altered thereby. The difference between the change of melting point with pressure for anorthite and that for albite may, however, be too high. In so far as the above assumptions hold good, the melting-point-pressure curve is practically a straight line, being slightly concave upward.

Since according to the above calculation, the increase of pressure raises the melting-point of orthoclase more than that of albite, it would shift the field boundary for a melt consisting of orthoclase and a highly sodic feldspar toward the orthoclase-side of the diagram. In order to approximate the amount of change in the equilibrium between orthoclase and albite, the following operation was carried out:

It was assumed that the eutectic Or : Ab is at 45Or : 55Ab, and that the temperature of the eutectic is 30° below the melting point of pure albite.[15] From these approximate data, a rough temperature-composition diagram was constructed (Fig. 3) by representing the two freezing-point curves by the straight lines AE and EB, passing through the eutectic point E and the respective melting points of the two components A and B. A second approximate diagram for the same components, at a pressure of 1000 atmospheres was constructed, according to the suggestion of Roozeboom[16], by drawing two new freezing-point curves, A′E′ and B′E′, each represented by a straight line, parallel, respectively, to AE and to BE, and passing through the respective melting points A′ and B′ of the two components at 1000 atmospheres, as calculated from the Clausius-Clapeyron equation. Thus we may locate approximately the position of the point E′, showing the composition

---

[15] Andersen, Olaf: private communication cited by J. H. L. Vogt, "The Physical Chemistry of the Magmatic Differentiation of Igneous Rocks," Nor. Vid. Ak, Skrifter, no. 4, p. 59, Oslo, 1926.

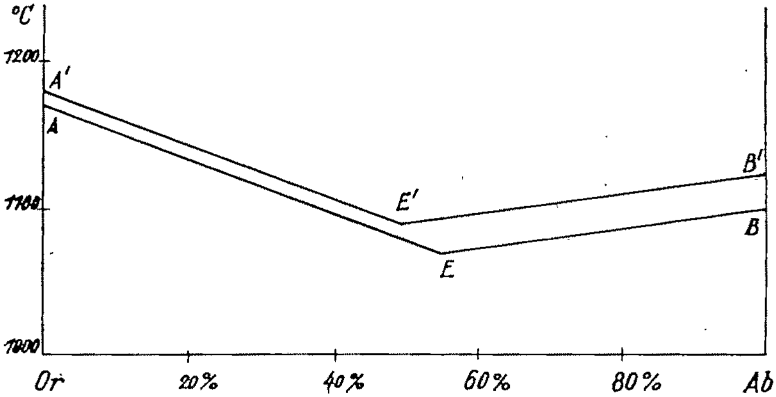


Fig. 3. The effect of pressure on equilibrium in the binary system Or: Ab. A and B represent the melting points of orthoclase and albite respectively, at atmospheric pressure, and E the corresponding (assumed) eutectic point; A′, B′ and E′ represent the same quantities calculated for 1000 atmospheres pressure.

and temperature of the eutectic orthoclase: albite at a pressure of 1000 atmospheres. According to the graphical solution carried out on the basis of the data given in Table I, E′ would be located 20° above E, or, on the basis of the above assumption regarding E, at about 1090° C., and contains about 6% more orthoclase than the eutectic at atmospheric pressure or 5% against the assumed 45%.

Probably everyone would agree that many granites have originated at depths of more than ten kilometers below the surface, under a pressure of several thousand atmospheres. On the basis of the above discussion, it seems possible that under these conditions, the eutectic Or: Ab, and to a somewhat less extent, the cotectic Or; sodic plagioclase may contain considerably more Or than at atmospheric pressure. The field boundary, however, between Or and a plagioclase of intermediate composition would not, as noted above, be significantly affected by pressure. Thus the occurrence of coarse-grained potash-rich rocks containing a sodic plagioclase, and the absence of any (with reference to Bowen's diagram) containing intermediate or calcic plagioclases, may be explained. Furthermore, the fact that deep-seated rocks have been produced under pressures of various intensities, and therefore, under various equilibrium conditions offers an explanation for the failure of coarse-grained rocks containing a sodic plagioclase to throw light on the position of the equilibrium boundary for atmospheric or any other one pressure.

---

[16] Roozeboom, B.: "Heterogene Gleichgewicht" II, p. 429 and Figs. 130 and 142, 1904.

THE PRODUCTION OF POTASH-RICH ROCKS BY THE ALTERATION OF SEDIMENTARY AND IGNEOUS TYPES.

Formation of "Granite" by the Feldspathization of Sedimentary Metamorphic Rocks. In his discussion of the silica content of igneous rocks, Bowen[17] says " 'Granites' of very high silica content may be the result of . . . . granitization of a highly siliceous rock such as quartzite." A number of recent articles[18] show that this mode of origin may account in many cases not only for a high silica content but also for an abnormally high potash content in rocks that possess all of the physical characteristics of ordinary granites, including, in at least one case, the intrusive relation to the country rock. These individual occurrences suggest that perhaps some of the other potash-rich granites, previously regarded as true igneous rocks, may have originated in a similar manner.

That a similar replacement process may take place in schist is shown by Brauns'[19] description of such rocks which have been more or less completely altered to sanidinite by the introduction of alkalis. Some of these contain a notable excess of potash feldspars over soda-rich plagioclase. Most of them, however, unlike the feldspathized quartzites described by the above-mentioned authors, retain vestiges of their original structure.

---

[17] Bowen, N. L.: op. cit., p. 131.

[18] Quirke, T. T.: "The Killarney Gneisses and Migmatites," Bull. Geol. Soc. Am., vol. 38, pp. 753-770, 1927.

———: "The Structures and Batholiths of French River Area," Jour. of Geol., vol. 37, pp. 683-699, 1929.

Daly, R. A.: "The Bushveld Igneous Complex of the Transvaal," Bull. Geol. Soc. Am., vol. 39, pp. 703-768, 1928. In this article, Daly refers to several other similar occurrences.

[19] Brauns, R.: "Die Mineralien der Niederrheinischen Vulkangebiet," p. 47. Stuttgart, 1922.

Increase of Potash-Soda Ratio of Normal Igneous Rocks in Connection with their Alteration. While the evidence is of a fragmentary nature, there is sufficient data at hand to suggest that during hydrothermal alteration and weathering, rather important amounts of potash may be added to normal igneous rocks, and, that if leaching occurs, soda and lime may be removed to a larger extent than is potash. While it may be argued that under ordinary circumstances such altered rocks are recognized and designated as such, it will be shown below that this is probably not always the case.

Although the available experimental evidence is somewhat meager, it suggests, as far as it goes, that weathering products tend strongly to take up potash. That soils may absorb this substance has long been recognized. F. W. Clarke[20] states that "as a rule, a soil takes up potash more readily than lime, magnesia or soda, and retains it more tenaciously." In a series of experiments, Dittrich[21] showed that when weathered granite is treated with a potassium salt solution, potassium tends to replace calcium and, to a less extent, sodium.

It is clearly impossible at this time to estimate either the relative importance of such processes occurring in nature under hydrothermal or weathering conditions, or the extent to which the products of such replacement may be taken for normal igneous rocks. However, I wish to cite a few examples which lead one to suspect that the process may be more prevalent than we have supposed.

Although it is not generally assumed that there is any connection between the alteration and devitrification of volcanic glasses, a comparison of the compositions of devitrified glasses with those of normal ones suggests, although of course it does not prove, that devitrification and alteration involving replacement or selective leaching or both, are two closely related processes. In Fig. 4 is presented a variation diagram of lime, soda, potash and water, plotted against silica, for normal and for devitrified glasses containing more than 70%

---

[20] Clarke, F. W.: "Data of Geochemistry," Bull. U. S. Geol. Surv., No. 695, p. 496, 1920.

[21] Dittrich, M.: "Chemisch-geologische Untersuchungen ueber 'Absorptionserscheinungen' bei zersetzten Gesteinen," Mitth. Grossh.-Bad. geol. Landesanstalt, vol. 4, p. 330, 1903.

silica, whose analyses are given in Washington's Tables.[22] It will be noted that the four devitrified glasses represented are distinctly richer in potash, and poorer in soda and lime than are the normal ones. This fact recalls the statement of Clarke with respect to soils, as well as Dittrich's experiments on weathered rocks, cited above, and suggests that devitrified glasses may have suffered a considerable amount of change in their chemical composition, through leaching out of soda and/or lime, or by the addition of potash. Their relatively high water-content is also in accordance with the hypothesis that they are altered. In addition to the general principle illustrated, the four devitrified glasses of Fig. 4 are of importance in themselves, since they are the only known rocks of (originally) glassy character whose composition lies in the orthoclase field of Bowen's equilibrium diagram.

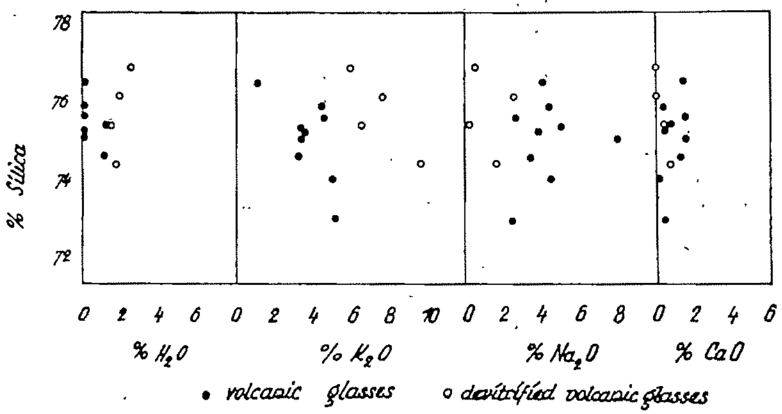


Fig. 4. Variation diagram of thirteen glassy rocks from Washington's Tables. Water not determined in two analyses.

In the present connection, a particularly interesting occurrence is that of the Mount Devon diabase porphyry,[23] which presents a good illustration of the replacement of soda and lime by potash. The very thorough investigation of the authors has shown that the phenocrysts of this rock, now containing 4.52% K_2O, originally consisted of a plagioclase having the approximate composition $Ab_{35}An_{65}$. Nevertheless, the general appearance of the rock was so misleading, that the term "devonite" has previously been proposed as a rock name for a "variety of porphyritic dolerite characterized by phenocrysts rich in potassium,"[24] the author of the term apparently having supposed that the K_2O was original, as did also the present author until convinced of the contrary by the data presented by Muilenberg and Goldich.

---

[22] Washington, H. S.: "Quantitative Classification of the Igneous Rocks," U. S. Geol. Surv., Prof. Paper No. 99, Washington, 1917. A few of the analyses given by Washington are not represented in the diagram, either because the original author did not state definitely whether or not the glass was devitrified, or else because the original reference was not available to the writer.

[23] Muilenburg, G. A., and Goldich, S. S.: "Petrography and Petrology of the Mount Devon Diabase Porphyry," this Journal, vol. 26, pp. 355-367, 1933.

In conclusion, I wish to thank Professor Esper S. Larsen of Harvard University, who has offered many helpful criticisms and suggestions during the preparation of this article.

---

[24] Holmes, Arthur: The Nomenclature of Petrology, p. 78, 1928.

TECHNISCHE HOCHSCHULE,
VIENNA, AUSTRIA.

DISCUSSION AND COMMUNICATION.

CLIMATES OF THE PLEISTOCENE: A REVIEW.

Attempts to explain the fundamental causes of extraordinary glacial times such as the Pleistocene bulk large in the literature of geology and meteorology. The early notion that broad uplift of continental areas is a cause adequate in itself has been abandoned by nearly all students of the problem. Hypotheses appealing to changes in the composition and dust content of the atmosphere have likewise met with little favor as fundamental factors. Attempted explanations on a basis of planetary and astronomic relationships have had wider appeal, and have underlain many discussions of the problem. The igneous hypothesis of Croll[1] and of Köppen-Milankovitch[2] require among other things that the times of lowered temperature in the northern hemisphere should have coincided with times of warmer conditions in the southern, a requirement that does not seem to be met by the facts so far as we know them. This difficulty is escaped by the postulate[3] put forward by Huntington in 1914 that the unusual climates of the Pleistocene were caused by variations in the amount of radiation emitted by the Sun. For two decades this notion has been discussed as a serious possibility. In a recent contribution to the problem,[4] Simpson has deduced the meteorologic and climatologic consequences of assumed variations in solar energy, bringing out a number of possible relationships that deserve wider recognition by geologists than their publication in a meteorologic journal is likely to secure.

Simpson's principal argument is qualitative, and runs thus (See figure): Increased solar radiation would raise the temperature at the Earth's surface, relatively more at the equator than at the poles, so increasing the atmospheric circulation, evaporation, cloudiness, and precipitation. Therefore in ice-free regions pluvial stages would coincide with times of maximum radiation, dry stages with minimum radiation. In ice-covered regions (such as the Antarctic), however, the effect of increased radiation would be different. Temperature and total precipitation would increase, and snowfall would increase for a time, but at a rate less rapid than evaporation and melting. Eventually a time would come when the annual accumulation of snow would decline, finally reaching zero. This sequence of events gives a glacial stage followed by a relatively warm wet interglacial. Decreasing radiation would reverse the process. Thus temperature, winds, evaporation, cloudiness, and precipitation would decrease, and the decreased temperature, evaporation, and melting would in time increase the proportion of snowfall in the total precipitation, the resulting accumulation of snow giving rise to another glacial stage. Total precipitation, however, would continue to decrease with decreasing temperature, eventually reducing the annual accumulation of snow so far as to end the glacial stage, replacing it with an interglacial stage not warm and wet, like the preceding interglacial, but cold and dry.

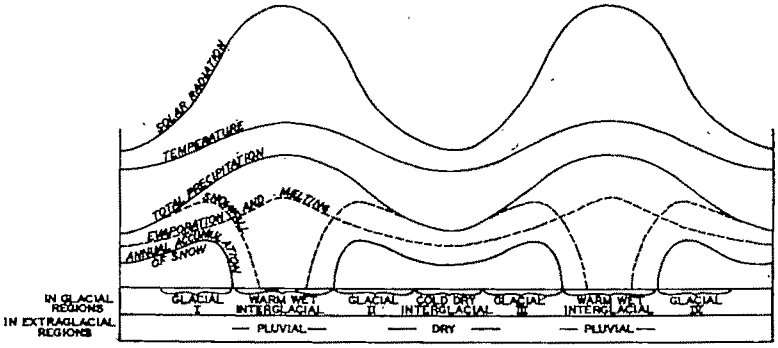
---

[1] Croll, James: Climate and time in their geologic relations. . . London, 1875.

[2] See Köppen, W., and Wegener, A.: Die Klimate der geologischen Vorzeit. Berlin: Gebr. Borntraeger, 1924.

[3] Huntington, E.: The solar hypothesis of climatic changes. Bull. Geol. Soc. Amer., Vol. 25, pp. 477-590, 1914.

[4] Simpson, G. C.: World climate during the Quaternary period. Quart. Journ. Roy. Meteorol. Soc., Vol. 60, pp. 425-471 (discussion, pp. 471-478), 1934.



Effect of two cycles of solar radiation on temperature, precipitation, snow accumulation, glaciation, and pluvial stages according to Simpson. (Combined from Simpson's Figs. 2 and 3.) The curves are qualitative only; all quantitative significance is specifically disclaimed.

It follows from this argument that the maxima of pluvial stages in non-glacial regions would not be synchronous with glacial stages in glacial regions, but would coincide with the warm wet interglacial stages.

The eccentric disposition of the glaciated regions around the North Pole, extending much farther south around the Atlantic than around the Pacific, is explained as follows: Increased precipitation at the Pole would form increased sea ice in the Arctic Ocean and on the surrounding lands would institute glaciers (including the Scandinavian and Labrador-Keewatin ice sheets) which would calve into this ocean. The Arctic ice would discharge only into the Atlantic between Greenland and Spitzbergen, cooling that ocean, shifting southward the North Atlantic "low," and thus giving prevailing NE rather than SW winds to northwestern Europe. The lowered temperature *plus* the increased precipitation deduced earlier, resulted in the appearance of ice sheets in Scotland, northern England, and Ireland. The floating ice debouching into the North Atlantic is pictured as forming a solid sheet somewhat like the Ross Barrier, welding North American ice to European ice. On the contrary, little or no ice could pass through the Bering Strait bottleneck into the Pacific, whose rising temperature due to increasing solar radiation was therefore not counteracted by ice chilling. (Note the conflict of this idea with the chilling of the Pacific involved in the Glacial-control theory of coral reefs!) Relatively little glaciation therefore affected the Pacific borders, and the glaciation that occurred was due to increased precipitation only, despite increased temperature.

Pleistocene glaciation of most of the mountains of the world is held to have been the result of increased precipitation, but the belief of Penck and Brückner that in the Alps Pleistocene precipitation was no greater than at present, is sustained on the ground that the position of the Alps just beyond the south margin of the Scandinavian ice sheet was unfavorable for increased precipitation, lowered temperature being there the causal factor.

On the quantitative side, Simpson calculates that a maximum temperature variation of 5° to 10° C., indicated by Pleistocene organic evidence, would require variation in solar radiation of 20 per cent on either side of the mean, the cycle of variation being of the order of a million years. This amount of variation is not as remarkable as it might at first seem, as solar radiation now varies by several per cent within a few days.[5]

In comparing the implications of this hypothesis with the geologic record, Simpson believes there are many agreements. He correlates the fourfold glaciation of the Alps and eastern North America with the four glacial stages embraced in two solar cycles, and holds that the existing evidence of interglacial stages is consistent with his deduced concept of two warm wet interglacials with an intervening cold dry interglacial. Using his deduction that the ice of the first and third glaciations disappeared by normal recession as a result of increased temperature, whereas the ice of the second and fourth glaciations disappeared by wasting down and becoming stagnant as a result of decreased precipitation, in spite of lowered temperature, he correlates this view with the widespread evidence of thin dead ice during the fourth deglaciation, and of thicker active ice during the third deglaciation. In this connection the conclusions of Scott and Meinardus are of great significance, that the Antarctic ice is now in a thin, sterile, and locally stagnant condition, and that its former thick, mobile, and vigorous condition could be restored only by *ameliorating* the present climate, which in Simpson's view is that of a cold dry interglacial. Again, the well-recognized postglacial optimum climate of several thousand years ago is held to support the deduced climatic curve by recording the diminishing effect of the waning glacial climate on a generally declining curve of temperature (see figure).

---

[5] See, for example, Moulton, F. R., *Astronomy*, New York, 1931, p. 337.

Some of these correlations, and others based on culture stages, met with criticism offered at the meeting at which the paper was read, and printed with the paper itself. The points criticized deal mainly with European data. Criticisms from the American field might be added, among them that although A. P. Coleman, the authority on the Toronto interglacial beds, thinks it probable that these beds with their warm fauna belong to the second interglacial, Simpson suggests correlation with the third interglacial. Again, the argument is put forward that loess was associated with every glaciation, and that all but the late-glacial loess has been removed by erosion. This view is held to be supported by the loess record in Europe and Asia, but the North American loess is neglected. It is scarcely consistent with the fact that a great volume of loess is associated with the Iowan glaciation, whereas very little is associated with the later Wisconsin drift. In another place the distinct Keewatin and Labrador ice centers are stated to be "simply secondary centers of the main ice sheet, and due to the local topography." It is not clear what topographic features are referred to by this statement, which fails to explain the existence of these two adjacent ice domes, a fact to which students of the American Pleistocene have long sought an answer.

The statement already referred to that in the northern hemisphere ice accumulated first in and around the Arctic Ocean is subject to the modification that driftless, non-glaciated areas of considerable size fringe the Arctic shores in Alaska and the lands to the east, and in Siberia.[6] Full acceptance of this view must therefore await an explanation of these apparent anomalies.

A question sure to be asked is why, if the Sun is a variable star, glacial times did not recur as frequently prior to the Pleistocene as during that epoch. Although Simpson himself favors harmonic variation in solar radiation, there is no evidence on this point. As variation may have been highly irregular, this does not constitute a serious objection to the hypothesis.

Nothing as complicated as the Pleistocene climates, can have had a simple cause. Simpson has chosen what is probably the most satisfactory way of attacking the problem: setting up a general hypothesis, deducing its consequences, and comparing these with the geologic record. No one student is familiar with so broad a field that he can make a full and adequate comparison, but if a hypothesis such as this is brought to the attention of specialists in the various fields involved, comparisons can be made readily, and the hypothesis can be accepted, modified, or rejected. Simpson's notion seems so promising, that although it requires modification it ought to be thoroughly examined in the light of (1) the number of glacial stages recorded in each region, (2) the climatic character of each interglacial, (3) the stratigraphy of the loess, (4) distribution areally and stratigraphically of stagnant ice in wasting ice sheets, (5) the climatic record contained in lake deposits in extraglacial regions, and (6) the cultural record. This will stimulate profitable thought in these fields, and should encourage investigation of such problems as the relative importance of increased precipitation and lowered temperature in the Pleistocene lowering of snowlines in the ranges of the North American Cordillera. RICHARD FOSTER FLINT.

---

[6] Antevs, E.: Maps of the Pleistocene glaciations. Bull. Geol. Soc. Amer., Vol. 40, pp. 651-654, 687-688, 1929. Capps, S. R.: Glaciation in Alaska, U. S. Geol. Survey, Prof. Paper 170, Pl. 2, 1931.

YALE UNIVERSITY,
NEW HAVEN, CONN.

SCIENTIFIC INTELLIGENCE.

CHEMISTRY AND PHYSICS.

The Spirit of Chemistry; An Introduction to Chemistry for Students of the Liberal Arts; by ALEXANDER FINDLAY, Professor of Chemistry, University of Aberdeen. Second edition. Pp. xvi, 510; 88 figs., 64 portraits and illustrations. 215 x 14 cm. London and New York, 1934 (Longmans, Green and Co., $4.00).—This edition is essentially identical with the first edition reviewed in this Journal in 1931[1] except that brief discussions of Moseley's atomic numbers, of the discovery of deuterium and of the properties of "heavy water" have been added together with new sections on coal-tar dyes and synthetic drugs and perfumes. In this edition also the condition of strong electrolytes in aqueous solution is presented from the modern view-point and neutralization reactions are discussed, a serious omission in the first edition.

Most of the errors, which are inevitable in a first edition, have been corrected but a new one appears on page 89 where the frequency is defined as "the reciprocal of the wave length, or equal to $1/\lambda$."

The reviewer recommends the edition as an excellent text for use in courses planned especially for liberal arts students.

JOHN A. TIMM.

Kleiner Grundriss der Theoretischen Physik; by ARTHUR HAAS. Pp. vii, 183; 22 figs. Berlin W10, 1934 (W. de Gruyter and Co., RM., 5.30).—In this little book Professor Haas has collected the more important results of theoretical physics for the student of physics who wishes them for review, or for the student of a related science who wants to survey the important conclusions of theoretical physics without following through their analytical deduction. The subject is divided into four parts: Mechanics, Theory of Electromagnetic Fields and of Light, Heat, and Atomic Theory. A knowledge of the calculus is assumed, and a little vector analysis and even some tensor analysis is introduced. While no effort is made to show in detail how the important laws of theoretical physics are deduced, the significance and the application of these laws are clearly explained. The book is quite up-to-date, treating the elements of the general relativity and of wave mechanics, as well as the classical physics. L. P.

GEOLOGY AND MINERALOGY.

The Geology of Parts of Southern Norway; by OLAF HOLTEDAHL, ARNE BUGGE, CARL F. KOLDERUP, HALVOR ROSENDAHL, JAKOB SCHETELIG, and LEIF STÖRMER. Proc. Geologists Assoc., vol. **45**, pt. 3, pp. 307-388, 33 pls., 48 figs., 1934.—Sixty members of the British Geologists' Association visited Norway last summer between August 2 and 15, and were shown the Pre-Cambrian, Cambro-Silurian, and Permian formations of southern Norway, with their structures (Caledonian orogeny and Permian faulting), by Holtedahl, Kolderup, and their assistants. The guide to the region, here published, gives an up-to-date account of its geology, by Norwegian workers, and American geologists who wish to know this geology will find it concisely described and well illustrated by line drawings, maps, and half tones. C. S.

---

[1] Series 5, vol. 22, p. 81, 1931.

Studien über Lamellibranchiaten des Leptaenakalkes in Dalarna: Beitrag zu einer Orientierung über die Muschelfauna im Ordovicium und Silur; by ORVAR ISBERG. Pp. 428, 32 pls., 9 figs., Lund, 1934.—This monumental volume, with its excellent plates of retouched photographs of carefully prepared specimens, is based on collections that the author has been making since 1916, together with material from other collections in Sweden. This great mass of primitive bivalves is derived from the Lower division (= Kullsberg or Platylichas zone) and the richly fossiliferous Upper division (= Kallholn or Holotrachelus zone) of the Leptaena limestone. Both are of reef origin. Isberg states that he was unable to collect his specimens from bed to bed, because of the methods of quarrying, and that the borrowed material likewise is known only to be from either the Lower or the Upper division of the Leptaenakalk. Furthermore, the bivalves from similar formations in other countries are as yet but little known, and accordingly he is unable to produce trustworthy stratigraphic correlations. Hence the value of the monograph lies in its carefully wrought out descriptions of the genera and species, and in the 32 pages devoted to the general morphology of the shell. The Lower division is of late Ordovician time, and the Upper is probably very early Silurian in age. These correlations are, however, based on trilobites studied by other paleontologists.

The author describes 180 species, not one of which has representation in both divisions. All but 3 are new species, and 7 are not named. They are largely edentulous bivalves, out of which the toothed shells arose. The species are grouped in 40 genera, 21 of which are new, and 11 families; 30 genera are restricted to the Upper division, 3 to the Lower, and 5 are common to both. Of the named species which occur in a zone that is known with certainty, 137 are restricted to the Upper division and 26 to the Lower. Therefore, as Isberg says, the Upper division shows an "explosive evolution" of these bivalves. Of these 40 genera, 16 are represented by a single species, and 9 by only two forms; and often the species are known only from single specimens.

This work is the greatest addition made in recent years to our knowledge of Paleozoic pelecypods, and we congratulate the author on his excellent results. C. S.

Report of the First Scientific Expedition to Manchoukuo, under the leadership of DR. SHIGEYASU TOKUNAGA.—The results of this Expedition, thus far given in three volumes, 7½ x 10½, are of especial interest since it was the first to visit and study minutely an important portion of the present expanded Japan, this includes the Jehol province. The text is given both in Japanese and in English, and many pages of excellent and interesting illustrations follow, as noted below. That every effort was made to have the work done thoroughly is obvious from the fact that the party included in all thirteen trained workers: six in geology, one in geography, three in botany, two in zoology and one in anthropology. The three parts already published are as follows:

SECTION I, by the leader of the expedition, mentioned above. This gives the details of the study of the country passed through, its inhabitants and their manner of life, also the structure of the country—in a word the science in general. The English text covers pages 45 to 76. Following these are 68 pages of excellent illustrations reproduced from photographs. In most cases a page includes six figures, and the total number thus falls little short of 400.

SECTION IV, PART I: by DRS. T. NAKAI and M. KITAGAWA, is devoted to the plants, chiefly of Jehol, the highland province in the southwest of Manchoukuo. Some 10,000 specimens were collected, of which about eight hundred, ligneous and herbaceous, were identified as to the species. The new Woody Plants are described by Dr. T. Nakai, the new Herbaceous Plants by him and Dr. M. Kitagawa. The illustrations, on a large scale, cover Plates I-XVIII. The expedition met with many hardships, due to the intense heat, to occasional floods, also to disease and bandits.

SECTION V, PART I, by TAMEZO MORI, presents the fresh-water fishes of Jehol. Seven hundred and eighty-three were collected and the prominent species are here described with fine figures on Plates I to XXI. In the majority of cases these are of natural size and in Plate I the *Acanthorhodeus jeholicus* is given in color in Figs. 1 and 2.

Getting Acquainted with Minerals; by GEORGE LETCHWORTH ENGLISH. Pp. xi, 324, 254 figs. Mineralogical Publishing Co., Rochester, N. Y.—Mr. English has for many years been the keenest and most important collector and distributor of minerals in the country. He has served all the big mineral collections and mineralogical laboratories and also has aided and encouraged the private collecting by amateurs. He is peculiarly fitted to write an introduction to the study of minerals such as this book. The early chapters are devoted to general matters: crystals, cleavage and fracture, structure, etc. Part II gives the description of the more important species. Part III includes a short description of the various important rock types, a set of determinative tables based on physical tests and a pronouncing vocabulary of mineral names. The book is very well printed and profusely illustrated by line drawings and reproductions of photographs. The latter are particularly well chosen and extraordinarily well done. The book should very successfully fulfill its purpose of interesting the beginner in the study and collecting of minerals. W. E. F.

MISCELLANEOUS SCIENTIFIC INTELLIGENCE.

Researches on Fungi; by A. H. REGINALD BULLER. Vol. V. Pp. xiii, 416; 174 figs. 1933, London and New York (Longmans, Green & Co., 25s. net).—Students will find this volume exceptionally stimulating to biological ideas. The purpose of clamp connections in the Hymenomycetes and Gasteromycetes is discussed showing that these organs give two passageways between adjacent cells for protoplasm instead of one, and that clamp connections always grow backward from the tip of a hypha and not forward so that the nucleo-plasmic ratio of the terminal cell is not disturbed. The rate of protoplasmic streaming through septa by means of the central pore is given. This pore permits protoplasm to move freely from cell to cell, but the pore can be closed instantly when an adjacent cell dies so that septa limit harmful influences of injuries to the mycelium.

Sporobolomyces, a yeast-like fungus, is clearly indicated as belonging to the Basidiomycetes because its conidia are produced and liberated in the same manner as the basidiospores of the Hymenomycetes and Uredineae. Also the sickle-shaped, so-called secondary conidia in Tilletia are true basidiospores for the same reason, while the long, slender primary conidia are highly specialized sterigmata. The mechanism of the Sphaerobolus gun is next described and a general summary concludes the volume. J. S. BOYCE.

Modes of Behavioral Adaptation in Chimpanzee to Multiple Choice Problems; by ROBERT M. YERKES. Pp. 108. Comparative Psychology Monographs, Vol. 10, No. 1. Baltimore, 1934 (The Johns Hopkins Press).—A detailed report on a long series of experiments to test the adaptive responses of four chimpanzees when confronted repeatedly with a multiple choice problem. The investigation shows that in the chimpanzee, as in man, habit may be the foe of progress, while open-mindedness is conducive to problem solution by discovery. W. R. C.

Food and Health; by HENRY C. SHERMAN. Pp. x, 296. New York, 1934 (The Macmillan Co., $2.50).—Professor Sherman's work, written in popular style, is valuable to the individual reader, being a recent authoritative statement of the choice of foods in the dietary and the advances science has made in the field of dietetics. He stresses particularly the greater need of "protective foods," those especially rich in mineral elements and vitamins. Equally as interesting is his concise and explicit chapter on the control of the body weight. The book explains how, through intelligent use of the guidance it offers, we can adjust and improve an already adequate dietary so as to build up higher degrees of positive health, buoyant as distinguished from merely passable health. The material is so clearly and readably presented, it should find many readers. It convinces us of the importance of well-balanced judgments in the daily choice and use of food. In appendices are given extensive tables of the composition of foods, showing distribution of protein, mineral elements and vitamins. The last appendix gives illustrative records of meals for a period of six months, using the principles outlined in the book.

Lexique Technique Anglais-Francais; by GUY MALGORN. 2d Edition. Pp. xxii, 256. Paris, 1934 (Gauthier-Villars 55 Quai des Grands-Augustins, 25 frs.).—This excellent volume opens with tables which give the relation of French and English units of measure, volume, etc. The dictionary proper includes the prominent technical French and English words and their equivalent in the other language. The subjects embraced are: Machine-tools, combustion-motors, aviation, electricity, metallurgy, etc. Many workers and students will come to appreciate the value of this concise lexicon.

OBITUARY.

DAVID WHITE.

DAVID WHITE, as he was affectionately known to an incredibly large circle of friends and admirers, passed away in his sleep during the night of February 6. Born at Palmyra, New York, July 1, 1862, he was christened Charles David, but dropped the first name when he came to Washington after getting his B.S. degree at Cornell in 1886. A year and a half later he married Elizabeth Houghton of Worcester, Massachusetts.

His first paleobotanical publications (1890) were on the Cretaceous of Gay Head, but he had already been working on what became his chosen field as is shown by the authoritative monograph on the Missouri Carboniferous floras published in 1899. He brought to his work an unusually keen and active mind and was never content with a mere description of fossils, but was interested in their interpretation in terms of environment, particularly climate, and their part in the formation of coal and petroleum. His published results range from pre-Cambrian Algal deposits, for which he was awarded the Walcott Medal of the National Academy in 1934, to Permian floras and climates, and he did much to promote the study of peat in this country.

During the decade 1912 to 1922, he was Chief Geologist of the U. S. Geological Survey and for over thirty years he was Curator of Paleobotany of the Smithsonian Institution. Those who knew him need no reminder of his lofty character or unfailing kindness to, and interest in others, but for the sake of the record it should be put down that he was a true gentleman who never unintentionally hurt another's feelings and who was a foster-father of all young geologists and a wise counsellor to all the rest.

He held honorary degrees from Cincinnati, Rochester, and Williams; was a Research Associate of the Carnegie Institution; Member of the American Philosophical Society and Fellow of the American Academy of Arts and Sciences; Home Secretary of the National Academy of Sciences from 1923-27 and its Vice-President since 1927. In 1923 he was President of the Geological Society of America, his presidential address being on "Gravity Observations from the Standpoint of Local Geology." This is illustrative of his wide interests, as is shown by his work on seed ferns, on regional carbonization, on the origin of coal and oil, to mention but a few of these. For many years he was Chairman of the Committee on Paleobotany of the National Research Council.

No geologist of his time had a wider influence on the scientific life of the nation, or took a more active part in that of its capital. As I survey his life *at its climax* it was truly admirable.

E. W. B.

OBITUARIES.

MR. KENNETH ARMSTRONG, a young Oxford graduate already associated with the Harvard President, Dr. James B. Conant, in work on chlorophyll problems, died on January 3 at the age of twenty-five. This was the result of an accident in the Austrian Tyrol.

DR. ARISTARCH A. BELOPOLSKY, the Russian astrophysicist, since 1910 an associate of the London Royal Astronomical Society, died on May 16 at the age of eighty.

DR. O. D. CHEWOLSON, distinguished professor of physics at Leningrad, died on May 11, 1934, at the age of eighty-two.

DR. FREDERICK AUGUSTUS DIXEY, the English entomologist, died on January 16 in his eightieth year.

DR. WILLIAM DUANE, emeritus professor of bio-physics at Harvard University, died on March 7 at the age of sixty-three.

DR. MICHAEL GRAHAM, the zoologist recently living at Madeira, died on January 28 at the age of ninety-five.

DR. WILLIAM HALE HERRICK, emeritus professor at the Pennsylvania State College, died on February 26 at the age of sixty-eight.

MRS. JANE LONGSTAFF, author of papers on Palaeozoic gastropod shells, died on January 19 at the age of seventy-nine. She was the widow of Dr. G. B. Longstaff, the well-known entomologist.

DR. JOHN ALEXANDER MATHEWS, the prominent steel metallurgist, died on January 11 at the age of sixty-two. It is said of him that for over thirty years he was in the first rank of American steel metallurgists of world-wide renown.

Dr. Cleophas Cisney O'Harra, professor of geology and mineralogy at the South Dakota School of Mines (1898-1911), and from 1911 president and professor of geology, died on February 21 at the age of sixty-eight. He was the author of the geology of Alleghany Co., Maryland, also of a number of papers describing the geology and mineral wealth of the Black Hills region. Several folios of his were published by the U. S. Geological Survey.

Dr. Dwight Porter, emeritus professor of hydraulic engineering at the Massachusetts Institute of Technology, died on February 26 in his eightieth year.

Dr. Michael Idvorsky Pupin, professor emeritus of Columbia University, died on March 12 in his seventy-seventh year. Born in Idvor, now in Yugo-Slavia, he came to this country at an early age. His rare intellectual ability soon gave him a position of prominence and his original investigations led to many important results especially in telephony, wireless telegraphy and X-ray photography. One of his discoveries is what is now known as the Pupin coil. The value and originality of his work brought him frequent recognition in the form of gold medals, honorary degrees and membership in many important scientific societies throughout the world.

Dr. Robert R. Rowley, formerly paleontologist with the Missouri Geological Survey, died on January 26 at the age of eighty-one.

Dr. Arthur Thomson, emeritus professor of anatomy at the University of Oxford, died on February 7 at the age of seventy-six.

PUBLICATIONS RECENTLY RECEIVED.

Carnegie Institution of Washington. Year Book No. 33, 1934.

Advance Notes on a New Theory of Light; Vision is an instantaneous phenomenon. The reason why we do not believe in the Successive Propagation of Light and why we can deny it, by Armando Paracampo. Pp. 13. Rio de Janeiro, 1935 (Therezopolis, Estado do Rio, Brazil).

Crystals and the Polarising Microscope; by N. H. Hartshorne and A. Stuart. London and New York, 1934 (Edw. Arnold & Co. and Longmans, Green & Co., $6.00).

The Mesozoic Palaeontology of British Somaliland. Part II of the Geology and Palaeontology of British Somaliland. (Crown Agents for the Colonies, 4, Millbank, London S.W. 1, Price 1-10s. net.)

The Philosophy of a Biologist; by J. S. Haldane. Oxford and New York, 1935 (At the Clarendon Press; Oxford University Press, $2.50).

New Pathways in Science; by Sir Arthur Eddington. Cambridge and New York, 1935 (The University Press; The Macmillan Co., $3.00).

Growth of Cells, Tumor Formation, and Decomposition of Water and Organic Material; by H. E. Jones. Glasgow, 1935 (John Smith & Son, 7/6 net).

Carnegie Institution of Washington. News Service Bulletin, Vol. III, Number 21. Star Explosions.

The Scientific Basis of Evolution; Thomas H. Morgan. Second Edition. New York, 1935 (W. W. Norton & Co., $3.50).

Ricerche di Biologia. Antonino Rodolico, 1911-1932. Florence, Italy, 1934 (Felice le Monnier).

CALCUTTA UNI
Sec. No........
Book No.......
LIBRARY

AMERICAN JOURNAL OF SCIENCE
MAY 1935

A STATISTICAL METHOD FOR THE COMPARISON OF HEAVY MINERAL SUITES.

LINCOLN DRYDEN.

INTRODUCTION.

In the following pages an attempt will be made to introduce a numerical method for the comparison of heavy mineral suites. It is believed that heavy mineral work offers a particularly favorable field for the use of such methods, since we are able, in that work, to measure and count the data used, instead of describing them verbally. This numerical comparison is a step on the way to the final objective—"correlation by heavy minerals." But before continuing with our paper we must have clearly in mind what this so familiar phrase means, in order that we do not confuse it with other phrases employing the word "correlation" in a quite different sense.

It is perhaps not often necessary to define terms in the introduction to a topic, but in this paper confusion is imminent unless three meanings of the word "correlation" are explained at the outset:

a. The word "correlation," without modifiers, will be given its usual geologic meaning: the determination of the synchrony of geologic rocks or formations. This determination is usually carried out by the paleontologic method, and we shall, when using the word alone and unmodified, mentally restrict ourselves to this way of establishing equivalence in age.

b. "Heavy mineral correlation," or "correlation by heavy minerals" involves an entirely different concept, although the process may lead to results quite analogous to those attained by the use of fossils. The rocks of an area are examined as to their heavy mineral residues, and if one formation or bed have some unique character therein, it may be possible to establish age equivalence of isolated exposures of that bed by examination of heavy mineral suites. The final decision as to whether an unknown suite belongs with a given series involves a balancing of a number of factors—a kind of mental gym-

AM. JOUR. SC.—FIFTH SERIES, VOL. XXIX, NO. 173, MAY, 1935.

nastics which will engage us later. But in any case, correlation by heavy minerals is likely to be less sure than correlation by fossils, and in our present state of knowledge in this country, one "zonal" fossil is likely to outweigh a thousand heavy mineral residues.

In this paper we shall not really get so far as to attempt "correlation by heavy minerals" (except for some general remarks on the method), but shall be occupied with some of the steps leading up to that final objective. For a very important part of the process is the actual comparison of one heavy mineral suite or residue with another, and the purpose of this communication is to introduce methods of comparison more accurate than the mere use of such words as "similar" or "dissimilar" or "like" or "unlike." But until we can explain this more precise, numerical notation, we shall say, when we examine two heavy mineral residues in order to discover their relationship that we are "comparing" them and the result of such "comparison" will be, tentatively, that they are "like" or "unlike" or "similar" or "dissimilar" or that they do or do not "resemble" one another.

c. It is perhaps unfortunate that there must be introduced into this discussion the phrases "statistical correlation" and "coefficient of correlation." In them the word "correlation" has absolutely nothing of its geologic meanings—more specifically, nothing whatever to do with geologic or any other kind of time. "Correlation" in a statistical sense means the comparison, by means of certain formulae, of sets of data—the answer being a number which, in some way, expresses the relationship between the two sets of variables. For example, if one were to present a statistician with a set of figures for the rainfall of Kansas during a number of years, and with another set for the yield of wheat for the same years and asked him if there were any relationship between the two sets of data, he would proceed to "correlate" them. His answer would be a number which is statistically a measure of the relationship or interdependence between the two sets of data.

METHODS OF COMPARISON AND "HEAVY MINERAL CORRELATION."

Workers in heavy minerals have been content to make comparison between suites by personal judgment only. Commonly the reader is presented with two or more sets of percentages of mineral species, with the decision that certain suites are "like" and that others are "unlike"—facts that the reader might be ashamed to say he cannot see from the figures given. Sometimes, however, the figures are so similar in the various samples that one has no hesitation in acquiescing in such judgment; again, they may be so dissimilar that we "feel" their lack of relationship.

Table I gives a series of such percentages; they are purely fictitious but might easily be duplicated from geologic literature. It is "apparent" that sample A is, in its heavy mineral character, similar to sample B, and it is also clear that samples C and D are quite dissimilar in that respect. But is D like A or B? And if so, how similar? Clearly, the percentages of zircon are about the same, staurolite in D somewhat low, garnet a little high, and epidote rather low. Which of these facts is the more important? Is the similarity in percentage of zircon enough to outweigh the dissimilarities, or must we say that D is quite unlike either A or B? But if it is unlike A and B, is it more unlike A, or more unlike B? It is impossible to tell by inspection which is the more important fact—all the more impossible as the number of mineral species is increased. But we *must* have a way of seeing these relationships quantitatively; they are absolutely fundamental for the comparison of mineral suites and to the problem of "correlation by heavy minerals."

TABLE I.

	Samples			
Mineral	A	B	C	D
Z	35	30	68	29
T	4	6	0	7
St	16	15	2	8
Si	5	7	18	8
G	3	1	3	12
E	28	30	0	20
K	6	8	8	11
R	3	3	1	5
C	0	0	0	0

Z = zircon, T = tourmaline, St = staurolite, Si = sillimanite, G = garnet, E = epidote, K = kyanite, R = rutile, C = chloritoid.

For what we really mean by "heavy mineral correlation" is that for two given rocks containing similar mineral suites, the net result is *as if* the distributive province, mode of transportation, environment of sedimentation, and other factors had been the same in the two cases. Such a supposed concatenation of events leading to similar mineral suites we think of as more likely to have happened in the two places at the same time. And the closer the samples be geographically the more favorably we look on such a theory. The whole method, then, is based on the degree of similarity of mineral suites—great similarity leading to the inference that the same cause has been at work in the two or more samples, and dissimilarity implying independent (and thereby, in a single basin of deposition, non-synchronous) origin. And yet we have had no way of expressing similarity except by juxtaposing columns of percentages, looking from one to another, and announcing that the suites are "like" or "unlike."

STATISTICAL CORRELATION OF HEAVY MINERAL SUITES.

Statisticians use a comparatively simple formula for comparing ordered sets of data. For example, suppose that we were to make a table of the ages and corresponding heights of a child, and were to find that they followed the imaginary figures given in Table II. If we were to examine these figures with no preconceived ideas as to the growth of children, we should say that there seems to be some connection between increasing age and increasing height. If there were no statistical correlation, increases in age would be accompanied by any random height. But whatever the actual figures be, the statistician could give a number to express the relationship between the two sets of data above.

TABLE II.

Age (yrs.)	Height (inches)
1	20
2	22
3	25
4	30
5	36
6	42
7	48
8	56
9	63

Tables of heavy mineral frequencies can be treated in exactly the same way. They can be ordered according to mineral species and, therefore, they can be compared by the methods of "statistical correlation." (Ordered data are those which can be arranged in a "natural" series according to time, space, or almost any other criterion. If, for example, we had been given the figures of height in Table II, but had not been told which height corresponded to which age, one could not have used the method we are describing.) Table III shows the percentages of certain minerals in three samples.

TABLE III.

	A	B	C
Z	28	28	62
T	21	21	1
St	9	9	7
Si	6	6	1
G	4	4	13
E	13	13	10
K	6	6	1
R	3	3	5
C	3	3	0

Using common sense alone, we see certain relationships. Between samples A and B we see the remarkable fact that the zircon percentages are the same—a fact which indicates some connection between the samples. This indication is increased when the tourmaline is found to be the same, and increased more and more as we go down the list of minerals. Our final decision would be that these two samples are as closely "alike" as it is possible to tell from their heavy mineral frequencies alone. But consider the relationship of sample A to sample C. It is manifest that the heavy mineral suites are "quite unlike," but surely there is some relationship between them. If there is no other similarity, they do contain the same mineral species, even if in different percentages. If the relationship between A and B is perfect, or 100%, could we indicate by some fraction or percentage the relation or "likeness" of A (or B) to C?

The "coefficient of correlation" r, for which the formula follows, will give us the means of answering such questions numerically.

$$r = \frac{\Sigma(XY) - nM_X M_Y}{\sqrt{(\Sigma(X^2) - nM_X^2)(\Sigma(Y^2) - nM_Y^2)}}$$

Σ is the sign for the summation of that to which it is prefixed.

n is the number of pairs of percentages to be used, i.e., in this work, the number of mineral species.

M is the mean of that to which it is prefixed.

X is any percentage from sample A.

Y is the *corresponding* percentage (i.e., of the same mineral species) from sample B.

	Sample A		Sample C		
	X	X^2	Y	Y^2	XY
Z	28	814	62	3844	1736
T	21	441	1	1	21
St	9	81	7	49	63.
Si	6	36	1	1	6
G	4	16	13	169	52
E	13	169	10	100	130
K	6	36	1	1	6
R	3	9	5	25	15
C	3	9	0	0	0
	9/93	1610	9/100	4190	2029.
	10.3	$= \Sigma X^2$	11.1	$= \Sigma Y^2$	$= \Sigma XY$
	$= M_X$		$= M_Y$		

$$nM_X^2 = 9(10.3)^2 = 954 \qquad nM_Y^2 = 9(11.1)^2 = 1107$$

$$nM_XM_Y = 9(10.3)(11.1) = 1029$$

The data from samples A and C, Table III, are given to illustrate the use of this formula. The X column shows the percentages of the various mineral species in sample A and the Y column the corresponding values from sample C. (It makes no difference in what order the X values are arranged, but once that order is decided on, there is no choice for the Y values—they must correspond, mineral species for mineral species, with the X values.) For example, zircon has a percentage of 28 in sample A and 62 in sample C, tourmaline 21 for A and 1 for C, staurolite 9 and 7, etc. The second, fourth, and fifth columns of figures are given for completeness; obviously the values X^2 and Y^2 and XY will be needed in the equation, and it is best to arrange the work systematically.

Starting to substitute the values in the equation, we need first the sum of the XY terms—given at the bottom of the XY column—2029. Then we multiply n (the number of mineral species—here 9) by the product of the mean of the X values by the mean of the Y values—equals 1029. Subtracting the latter number from the former we have 1000 as numerator. A similar simple substitution in the denominator gives us the figures below:

$$r = \frac{2029 - 1029}{\sqrt{(1610 - 954)(4190 - 1107)}} = \frac{1000}{1422} = .70$$

The use of the "coefficient of correlation, *r*, in geologic problems, however, is open to two rather serious objections: a. the statistical word "correlation" is almost sure to suggest to the geologist something concerning the age equivalence of beds, and is certain to cause confusion if used at all loosely; b. values of the coefficient of correlation cannot be compared with one another as simple percentages. For example, we have found that two suites, of samples A and C, have a number, .70, which represents the similarity of the two. Suppose that we were to take two other samples, M and N, and were to find that their coefficient of correlation was, let us say, .40. We could not say, using this coefficient, that A is more similar to C than M is to N in the ratio of .70 to .40. But this is the very sort of comparison we want to make in our geologic problems—and it can be attained with but slight additional labor.

Both of the objections just presented can be obviated by the use of the "coefficient of determination"—which is equal to the square of the "coefficient of correlation." By using r^2 instead of r we can finally drop the word "correlation" in a statistical sense, but, more important, we now get a simple percentage as an expression of the proportion of elements common to the two samples or suites. Thus, in comparing suites of samples A and C, $r^2 = (.70)^2 = .49$, and this figure may truly be said to be the percentage of elements of A common to C, and, by simple subtraction, .51 the percentage or fraction of elements not common to the two. Furthermore, r^2 for samples M and N $= (.40)^2 = .16$; not only can we say that this figure measures the similarity of M and N in a like manner, but we can say that A is more closely related to C than M is to N in the ratio of .49 to .16. For our geologic purposes, then, we can say that A and C contain about three times more common elements than do M and N. Obviously such a numerical comparison is valuable; but before we suggest certain uses for the coefficient of determination it will be best to point out some of its attributes:

1. r^2 in heavy mineral work will, in general, be large, i.e., have a value between .50 and 1.00. This results from the fact that there are a rather small number of ordinary heavy minerals, and in any two samples a large proportion will be common to the two. If no species are common to the two, r^2 is 0; if some or all of the species are common, the value of r^2 depends on the frequencies found, varying from 0 to a maximum possible value of 1.00 when the percentages are identical.

2. The absolute value of r^2 means very little at the present time. When a considerable body of data has been accumulated the absolute value may be of some significance, but at

the present time r^2 for two samples is of importance only in relation to the r^2 for other samples.

3. The value of r (and thereby that of r^2) is affected by every percentage in each of the two sets, whether that percentage be large or small. If a species is not present in one sample its percentage is 0%, and this number is used just as is any other figure, and has just as much effect as any other in determining r, and hence r^2.

4. Varieties of mineral species are very important, in that each recognizable mineral variety should be treated in the formula as a separate mineral species. For example: if a sample contains long, thin, zoned zircons; short and stumpy, unzoned zircon, and purple zircon, there are, for statistical purposes, three kinds of zircon, which might be listed as "zircon A," "zircon B," and "zircon C" in the table of frequencies. If the second sample contains only the type "zircon A," the other two types must be put down as present to the extent of 0%. Varieties, then, increase the number of species used in the formula, and affect the reliability of r (and hence r^2)—as will be discussed immediately below.

5. The reliability of almost any statistical method increases with the number of observations—generally not in direct proportion, but as the square root of that number. Thus, 16 observations (or mineral species) will give twice the reliability or accuracy that 4 species or observations afford. The formula for the probable error of r will make this more clear than will any amount of description:

$$\text{p. e. of } r = \frac{.6745(1\text{-}r^2)}{\sqrt{n}}$$

We can use the results of the statistical correlation of samples A and C (given previously) to show the use and meaning of this formula. The coefficient of correlation, r, for the two samples was found to be .70, and the number of species, n, to be nine. Substituting we have

$$\text{p. e. of } r = \frac{.6745\ (1\text{-}(.70^2))}{\sqrt{9}} = .11$$

The meaning of this value is as follows: if we were to take two other samples of the same material and attempt to repeat this statistical correlation the chances are 50 out of 100 that the new value we should get would lie within the range

.70 ± .11, in other words, would not be less than .59, nor more than .81. The probable error decreases with an increase in n or r (or both). For two given samples n can be increased by increasing the number of mineral varieties recognized. But since the square root of n is involved, the effects of changes in this value will not be so potent in decreasing the probable error as will increases in the value of r. A practical way of increasing the value of r is to take more and more closely spaced samples, the limit of this process being two heavy mineral separations from the same small sample. Closely spaced samples, then, give us for r (and hence r^2) a value which is large, and which has a small probable error.

USES OF THE COEFFICIENT OF DETERMINATION, r^2.

To the potential users of this method of comparison of heavy mineral suites the writer wishes to offer warning against either of two extreme views: a. that the coefficient of determination will, in some way, take the place of common sense. For example, one cannot say that two samples from widely separated regions have had the same cause or origin just because the coefficient of correlation for the two happens to be high. No matter what value r^2 has, we know that samples from different basins of deposition have had very little to do with one another, and we should not pervert statistics to prove something we know to be impossible. b. that the accuracy of all our other measurements does not warrant the use of such a formula—that the whole method is too visionary and impractical. The writer is much more prone to subscribe to this objection than to the first, but he believes that in certain cases the method can be shown to be useful. We now know, or shall know, the errors inherent in the various procedures from sampling to counting grains in our slides, and there is no good reason why we cannot obtain percentages which are just as accurate as the present method of statistical correlation demands.[1] Indeed, almost any desired accuracy can be obtained

---

[1] Krumbein, W. C.: The probable error of sampling sediments for mechanical analysis: this Journal, 27, 204-214, 1934. (This paper was not written with heavy mineral work in mind, but the same or a similar method should be applicable.)

Rubey, William W.: The size-distribution of heavy minerals within a water-laid sandstone: Jour. Sedim. Petrol., 3, 3-29, 1933. Rubey's work shows that, in the general case, to compare two samples as to their heavy mineral content, two suites from two grade sizes of one sample must be in the laboratory. What is badly needed is more detailed field work, more samples taken over smaller areas, and an avoidance of the broad petrographic generalizations that have characterized most of our "correlation by heavy minerals." An example of a special kind of detailed work in which the statistical method is useful follows below:

The writer has been examining petrographically the contact between the Eocene and Miocene beds in Maryland. The Eocene below the contact shows a rather uniform suite of heavy minerals. Zircon and staurolite are the two most common, and each is present to the extent of 30 to 35%. The Miocene beds above the sharply marked contact are characterized throughout a thickness of 100-200 feet by a suite with some 50% of zircon, 15% staurolite, and 10% each of garnet and epidote. But from the contact to about one foot above it, the amount of staurolite in the Miocene rises to some 30%, the same percentage as in the Eocene beds below. This fact seemed very significant, since nowhere else in the Miocene (one exception—just above another contact) was such a large percentage of staurolite found. Table IV shows the remarkable resemblance of suites of average samples taken from the contact to one foot below, and from the contact to one foot above, Eocene and Miocene, respectively, Popes Creek, Maryland. The meaning of such an increase in staurolite near the contact would be given with almost no hesitation: it is that the Eocene material has been reworked into the base of the Miocene. That is just what one would expect with such unconsolidated sands as are present, particularly when one knows from paleontologic evidence that the contact is an unconformable one.

---

compared with two suites from the same or corresponding grade sizes of the other sample. Two values of coefficient of determination will be obtained from these comparisons. The value desired will be the mean of these two,—a value which will express statistically the percentage of elements common to both samples.

Ewing, C. J. C.: A comparison of the methods of heavy mineral separation: Geol. Mag., **68**, 136-140, 1931.

Otto, George H.: Comparative tests of several methods of sampling heavy mineral concentrates: Jour. Sedim. Petrol., **3**, 30-39, 1933.

Dryden, A. L., Jr.: Accuracy in percentage representation of heavy mineral frequencies: Proc. Nat. Acad. Sci., **17**, 233-238, 1931. (Note error in this paper: line 23, page 235, should read "55.3% or 64.7% as 60%.")

TABLE IV.

	Eocene	Miocene
Z	34	35
T	6	7
St	33	29
Si	½	2
G	½	13
E	6	6
K	2	2
R	13	6
C	4	½

Only one fact led to doubt in accepting this tacit conclusion. The staurolite of the Miocene had such characters that they seemed impossible of derivation from the Eocene. Thus, the overlying staurolite seemed fresher, larger, and of slightly different color. Still, there was that striking testimony of the similar percentages, and the writer was about to dismiss the problem and trust to figures rather than to indefinite varietal characters. Having opportunity to revisit the locality, however, he decided to find in a little more detail just where and how the mineral change from typical Eocene to typical Miocene took place. With a rather hazy idea of what was demanded in the way of samples, collections were made from the top inch of the Eocene (if there had been reworking at this place the material farther down could have had nothing to do with it), from one-inch intervals from the contact to 6 inches above the contact, and one sample from 6-9 inches and one from 9-12 inches above the contact. The heavy mineral suites of these samples yielded the figures given in Table V.

TABLE V.

		Z	T	St	Si	G	E	K	R	C
Miocene	12″									
		41	3	25	2	19	3	1	3	3
	9″									
		29	7	29	5	17	4	3	4	2
	6″									
		26	5	32	0	22	7	2	3	3
	5″									
		31	6	33	2	18	3	2	3	2
	4″									
		28	6	33	1	20	7	2	2	1
	3″									
		30	4	31	3	20	5	5	2	0
	2″									
		30	5	33	1	18	3	3	3	4
	1″									
		28	6	36	1	20	7	1	1	0
Eocene	0″									
		50	5	24	1	6	6	1	5	2
	–1″									

This table is just the sort one is supposed to understand at a glance, and from that glance to tell what samples are similar and what dissimilar. Many papers on heavy minerals present just as difficult a series of data, and stretch the credulity of the reader by pronouncing similarities and dissimilarities. It is true that in the present case one can see that this more detailed examination has changed the picture completely. It *can* be seen that the Eocene sample is quite different from the nearest Miocene one (0-1 inch) and that it resembles more the farthest one (9-12 inch). But we wish more information than

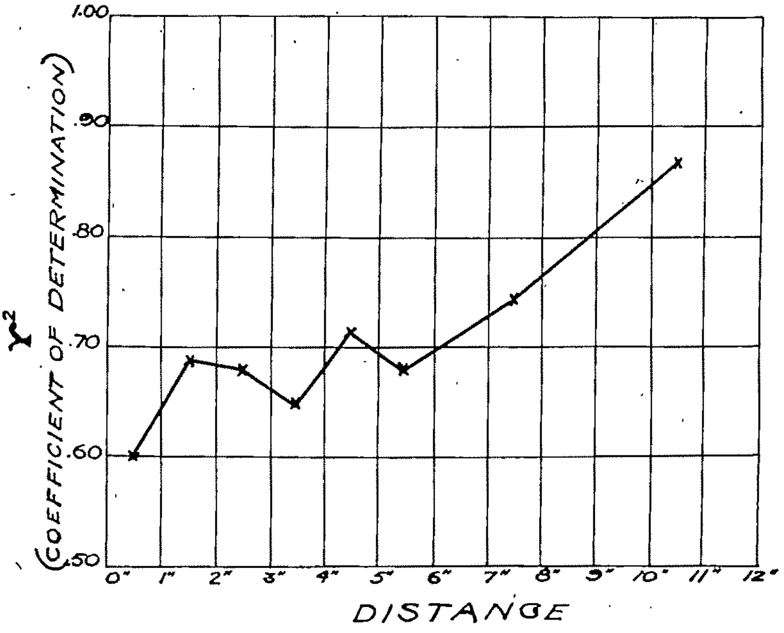


Fig. 1.

that: are there any samples more closely related to the Eocene than the 9-12 inch one? Are there any more unlike it than the 0-1 inch sample? And, more important, are the Miocene suites related in any regular or progressive sort of way to the Eocene one, or are our figures a purely haphazard collection?

It is believed that mere inspection will not answer these questions. And still more true would this be were we dealing with fifty samples rather than with nine. But if we plot a curve as a graphic expression of these figures we shall be able to see at a glance what the relations are. Fig. 1 shows such a curve, in which the value of r^2 (coefficient of determination) is plotted as ordinate and the distance of the sample above the contact as abscissa. The value of r^2 is taken each time between the Eocene suite and that of the successively more remote Miocene samples. The Eocene and the 0-1 inch Miocene samples have an r^2 equal to .60, the first point on our curve; the Eocene and the next (1-2 inch) sample have r^2 equal to .68, and the other values of r^2 are shown by small cross-marks on the curve.

(For those who may wish a more detailed exposition of the construction of this curve the following is given: the objective is to get the relationship between the Eocene sample and the 0-1 inch Miocene sample, then the relationship between the Eocene sample and the 1-2 inch Miocene sample, etc., until we have the values for the relationship of the Eocene sample and each one of the Miocene samples. We can arrange (or plot) these values in proper order, one coördinate being the amount of relationship, (r^2), and the other the distance of the sample from the Eocene-Miocene contact. To get the first value we follow the method outlined on a previous page for finding the relationship of samples A and C, Table III. But now we shall use the Eocene percentages (which are 50, 5, 24, 1, 6, 6, 1, 5, and 2) as the X values, and the corresponding 0-1 inch Miocene percentages (which are 28, 6, 36, 1, 20, 70, 1, 1, and 0, respectively) as the Y values. The same operation is carried out: the X^2 values and Y^2 values and XY values are calculated, and n equals 9, as before; substitution is made in the formula for r and that value obtained. For the Eocene and 0-1 inch Miocene samples it is found to be .78, approximately. r^2 is then $.78^2$ or .60, and this is the value of the coefficient of determination for the Eocene sample and the 0-1 inch Miocene sample, and it is plotted at the middle of the 0-1 inch interval. Next the value of r for the Eocene sample and the 1-2 inch Miocene sample is found. In this operation the X values stay just the same as before since we are again going to compare the same Eocene sample with a Miocene sample. All the values which have nothing but X, or X and n, in them are the same (for example, X^2 M_x, and nM_x^2). The Y's, however, are now the corresponding percentages from the 1-2 inch Miocene sample, which are 30, 5, 33, 1, 18, 3, 3, 3, and 4, respectively. Calculation of r for the Eocene sample and the 1-2 inch Miocene sample gives us the value of .82 (about); r^2 is, then, $.82^2$, or .68, and this value is plotted in the middle of the 1-2 inch interval. This operation is repeated for the 2-3 inch, 3-4 inch, etc., samples (eight times in all) and we obtain altogether eight values of r^2, which are plotted at their proper distances. r^2 for the Eocene and the 6-9 inch sample is plotted at the middle of the interval—at 7½ inches, and the 9-12 inch value, similarly, at 10½ inches.)

This curve shows clearly that the Miocene sample lying next to the Eocene differs most widely from the Eocene, and that the progressively more remote samples are progressively (with slight exception) more closely related to the Eocene. Reworking of Eocene material into the base of the Miocene appears, at this locality, as highly improbable, and basis for two statements about the staurolite percentages is given: a. that entirely too much attention was given to the mineral staurolite because of the similarity of percentages; b. that doubt as to the identity of the varieties of staurolite in the Eocene and Miocene was fully justified. At the beginning of Miocene sedimentation an evanescent source of staurolite was undergoing erosion; so far as the present information goes, there is no causal connection between the high percentages of this mineral in contiguous beds of the Eocene and Miocene.

Though one would arrive at a similar answer, the data of the preceding problem would not have to be handled in just that way. It would be perfectly possible and just as correct to calculate r^2 for each pair of contiguous samples, and then to plot these values against the distance from some arbitrary point in the outcrop. Indeed, if one were seeking to determine just where the greatest mineral break occurred in the Eocene-Miocene exposure described above, probably the best method would be to collect 1-inch samples from, say, the foot below the contact, and 1-inch samples from a foot or two above. Then calculate the r^2 between each neighboring pair of inch samples of the Eocene, then that between the top sample of the Eocene and the bottom one of the Miocene, and then the values for the pairs of Miocene samples. Probably the values of r^2 for the pairs of Eocene samples would be quite high, and when they were plotted against distance in inches, they would run along a more or less straight (horizontal) line at a value, let us imagine, of about .80 or .90. The value of r^2 between the topmost Eocene and lowest Miocene samples is known: it is the first value in Fig. 1—.60—a figure much lower than any of the preceding values on this imaginary curve. Then the Miocene pairs would give very high values of r^2 (that for the 1-2 inch and 2-3 inch samples is known to be .97), and these would, again, plot as a straight (horizontal) line at a value of .90 or more. The whole curve would be a nearly horizontal line, with, at one point, its course broken by a sharp dip or "valley." And the sharp break of the curve would give us the point (or almost the exact point) of greatest change in heavy minerals; this would be the contact based on mineral suites, irrespective of its position on any other criterion.

The example above, and the discussion of the whole method have not taken cognizance of two things familiar to all workers in heavy minerals:

1. The use of information above and beyond that of mere frequencies. The writer has not attempted to consider this matter at all. Facts known in some other way—by the aid of paleontology, or from workers in igneous rocks of nearby areas—may outweigh the information given us by comparison of mineral suites; the value of such outside facts is so great as to be self-evident.

2. The use of this method of comparison in "ordinary" correlation by heavy minerals. Many workers in heavy minerals collect their samples over an area of 10, 100, or 1000 square miles, at intervals of anywhere from one-quarter mile to 10 miles apart. The total number of samples may vary from 10 to 100 or more. Usually they come from a formation lithologically or paleontologically determined, but more precise vertical distribution is not attempted. The samples are worked over and percentages of frequencies are given—percentages often differing widely among themselves—which are said to typify the formation in question. Then the suite from an unknown sample is compared with that or those from a "known" sample or samples; if the agreement is close, or if they are very "like," the unknown may be said to come from the formation investigated. If they are "unlike," they are regarded as having come from different basins of deposition, or to have originated during different sedimentary cycles.

The writer is, unfortunately, not in a position to be critical of this type of work, and he knows that often no other is possible. He has described the method of work in order to point out the kind of heavy mineral investigation in which our statistical methods are inapplicable. There is nothing fundamentally wrong with that way of "correlating" by heavy minerals; it is the field work—the sampling, that must be improved before it will be worthwhile to treat the results statistically. It should be possible to sample a small area so thoroughly that one could, with confidence, average the mineral frequencies from the various samples, and then be able to say, in numbers, the chances that an unknown sample fits into the known samples. This is but one possible way of achieving this result; but no matter what the method, if one desires to use statistical formulae there must be a large enough number of *surely* related samples so that statistical comparison of unknown samples will be reliable and valid.

The writer would recommend the use of the coefficient of determination only in those cases where there are a number of causally or genetically related samples—excluding thereby most of the "ordinary" heavy mineral correlation. The use of the coefficient should prove of value in the study of contacts of sedimentary beds and problems of reworking of sediments (as outlined above), for comparing numerically the results of mechanical analysis (using percentages arranged according to sieves instead of mineral species), and in various field and laboratory studies of the details of sedimentation. One example of the latter might be a study of the relation of coefficient of determination to current velocity—a study that could be carried out in a laboratory of sedimentation. From this study one could learn to what extent changes of current might be responsible for changes in heavy mineral suites.

CONCLUSION.

The most simple and probably least important use of the coefficient of determination is as a *number* to take the place of a word or words in comparing two samples known by their heavy mineral frequencies only. But as the number of samples increases, and as greater and greater information about them is learned in the field, numerical comparison becomes more and more important and wholly supersedes visual inspection in value. As such information accumulates, it is believed that it will help in the explanation of sedimentary processes, and in correlation by heavy minerals.

ACKNOWLEDGMENTS.

The writer wishes to acknowledge his great indebtedness to Dr. Harry Helson, Professor of Psychology in Bryn Mawr College. Dr. Helson introduced the writer to the statistical methods outlined in this paper and he has, in addition, read the manuscript and suggested many improvements in form and content.

Bryn Mawr College,
Bryn Mawr, Pa.

CONTRIBUTION TO THE INTERPRETATION OF MINERAL FACIES IN METAMORPHIC ROCKS.

F. J. TURNER.

MINERAL FACIES IN METAMORPHIC ROCKS.

Metamorphism is essentially a process of mineral reconstitution and recrystallisation by which an assemblage of minerals is produced, whose members are in a state of mutual chemical equilibrium under the particular conditions (e.g. of temperature and stress) obtaining during metamorphism. Actually such equilibrium is by no means invariably attained; but Harker[1] has pointed out that reconstitution is always in the direction of restoring equilibrium, and that this appears to be reached more rapidly and to be more closely approached than is usually the case in a rock formed from crystallisation of a magma. The recognition of equilibrium assemblages of minerals is thus of fundamental importance in metamorphic petrology, and has been especially emphasized by Goldschmidt,[2] Eskola,[3] Tilley[4] and Vogt.[5] The term mineral facies or metamorphic facies was introduced in this connection by Eskola,[3] to include any group of rocks whose members (often varying considerably in chemical and mineralogical composition) had reached a condition of internal chemical equilibrium under particular conditions of temperature and stress. In other words, a metamorphic facies includes a number of equilibrium assemblages corresponding to a particular grade of metamorphism.

The application of the facies principle is complicated by lack of precise knowledge as to the exact ranges of physical conditions over which even well-known mineral assemblages are stable, as well as by the presence in some metamorphic rocks of disequilibrium assemblages containing one or more metastable members (cf. Eskola[6]). According to Eskola and Vogt, however, the essential criterion of a true equilibrium

---

[1] Harker, A.: Metamorphism, London, Methuen and Company, p. 10, 1932.

[2] Goldschmidt, V. M.: Die Kontaktmetamorphose in Kristianiagebiet, Vidensk. Skr., 1911.

[3] Eskola, P.: The Mineral Facies of Rocks, Norsk. Geol. Tidsskr., 6, pp. 143-194, 1920.

[4] Tilley, C. E.: The Facies Classification of Metamorphic Rocks, Geol. Mag., 61, pp. 167-171, 1924.

[5] Vogt, T.: Sulitelmafeltets Geologi og Petrografi, Norges Geol. Undersökelse, No. 121, 1927.

[6] Eskola, P.: The Mineral Development of Basic Rocks in the Karelian Formations, Fennia, 45, No. 19, p. 74, 1925.

Am. Jour. Sc.—Fifth Series, Vol. XXIX, No. 173, May, 1935.
27

assemblage is that for a given bulk composition it depends solely upon the conditions of temperature, stress, and pressure which obtained during crystallisation, and is independent either of the mineralogical nature of the parent rock prior to metamorphism or of the course taken by the metamorphism. This is undoubtedly true in ideal cases where purely physical conditions such as temperature and stress are the only variables, and where the concentration of such substances as water and carbon dioxide are constant throughout the change. But in many instances, and especially at low grades of metamorphism, water plays a vital part in reconstitution,[7] and hence variation in the amount of water present and in the extent to which it is capable of promoting metamorphic diffusion must then be taken into account in interpreting the equilibria in question. Further, the function of water in metamorphic reconstitution is to some extent dependent upon whether chemical readjustment takes place in response to rising or to falling temperature, and this in turn is determined partly by the state of internal equilibrium of the initial unmetamorphosed rock.

It is not the object of the present paper to present a complete analysis of the problem but rather to draw attention to the desirability of taking into account other factors besides temperature, stress, and pressure, in defining equilibrium mineral assemblages and metamorphic facies.

EQUILIBRIUM ASSEMBLAGES IN INITIAL ROCKS.

The assemblage of minerals which constitutes an initial rock prior to metamorphism may exhibit any of three states of equilibrium:

(1) The initial equilibrium assemblage corresponds to a lower temperature than that at which metamorphism is subsequently effected. Reconstitution will thus take place in response to rising temperature. To this category belong low-grade metamorphic rocks prior to suffering further metamorphism at higher grade. Harker[8] has drawn attention to the fact that low-temperature equilibrium is also closely approached in argillaceous sediments.

(2) The initial equilibrium assemblage corresponds to a higher temperature than that at which metamorphism is subsequently effected, so that metamorphism takes the form of

---

[7] Cf. Vogt, T.: op. cit., p. 516.
Hess, H. H.: Hydrothermal Metamorphism of an Ultrabasic Intrusive at Schuyler, Virginia, this Journal, 26, pp. 377-408, 1933.

[8] Op. cit., p. 48.

reconstitution with respect to falling temperature. Assemblages of this type are exemplified by unaltered igneous and especially volcanic rocks, and by high-grade schists prior to diaphthoresis. Some sediments, such as greywackes, derived directly from igneous rocks by rapid mechanical disintegration with little or no chemical weathering, approximate to this type of equilibrium.

(3) In many cases the component minerals constitute a disequilibrium assemblage, as for example in certain sedimentary rocks (cf. Harker[9]). Here the first stage in metamorphism is the establishment of equilibrium, by an often complex reconstitution process which may be in response partly to rising and partly to falling temperature. In this way the rock is brought into one or other of the two categories already decribed, and thereafter metamorphism proceeds accordingly.

METAMORPHISM BY ADJUSTMENT TO INCREASED TEMPERATURE.

Many of the best known instances of metamorphism involve reconstitution of initially low-temperature assemblages at higher temperatures, which may be accompanied by increased stress or hydrostatic pressure. Here may be included thermal and dynamothermal metamorphism of low-temperature sedimentary equilibrium assemblages (e.g. argillaceous sediments), and all but the initial stages of progressive metamorphism of rocks which were composed initially of either disequilibrium or high-temperature equilibrium associations of minerals. A few simple illustrations are given below:

(1) Progressive thermal metamorphism of an argillaceous sediment (compare Harker[10]).

Sericite-chlorite-quartz-iron ore-kaolin.
↓
Biotite-muscovite-andalusite-quartz.
↓
Biotite-orthoclase-andalusite-quartz.
↓
Orthoclase-hypersthene-sillimanite-quartz-cordierite.

(2) Progressive thermal metamorphism of marble containing small amounts of MgO, Al_2O_3, and SiO_2, as described by G. D. Osborne.[11]

---

[9] Op. cit., p. 79.

[10] Op. cit., pp. 48-59.

[11] Osborne, G. D.: The Metamorphosed Limestones and Associated Contaminated Igneous Rocks of the Carlingford District, Co. Louth, Geol. Mag., **69**, pp. 214, 221, 1932.

Calcite-clinozoisite-hornblende.
↓
Calcite-grossularite-diopside.
↓
Calcite-grossularite-diopside-wollastonite.

(3) Progressive dynamothermal metamorphism of quartzo-feldspathic sedimentary schists from South Westland, New Zealand.[12]

Quartz-albite-epidote-sericite-chlorite.
↓
Quartz-albite-biotite-clinozoisite-muscovite.
↓
Quartz-oligoclase-biotite-muscovite.

All of these changes involve progressive elimination of water from the system, since minerals containing hydroxyl are less conspicuous in the high-temperature than in the low-temperature assemblages. Since in most cases the water is free to escape, it follows that the presence or absence of additional water is relatively unimportant in determining the course of metamorphism of this type, and simple adjustment to variable conditions of temperature and stress is thus generally approached. Occasionally, however, the nature of the ultimate assemblage may be considerably modified by the quantity of water present. This is especially true of deep-seated metamorphism. Thus Harker[13] states that in the presence of abundant water biotite may persist in quantity to the highest grade of thermal metamorphism of pelitic rocks, though usually when less water is available it breaks down to a mixture of orthoclase, hypersthene, and some aluminous silicate. Again Tilley[14] has suggested that the alternative development of orthoclase-cordierite and muscovite-garnet in contact aureoles may depend, in part at any rate, upon the relative "dryness" of the rocks under consideration.

METAMORPHISM BY ADJUSTMENT TO DECREASED TEMPERATURE.

It frequently happens that a high-temperature equilibrium assemblage (as for example in an igneous rock, a greywacke, or a high-grade schist) suffers reconstitution at some relatively low temperature to give a second equilibrium assemblage. Such metamorphism may be dynamic (cataclastic), thermal, or more usually dynamothermal, according to the relative importance of temperature and stress in the process. It should be noted that though the mineralogical changes in the initial stage of progressive metamorphism may be of this type (e.g. in the transition from greywacke to low-grade schist), once a low-temperature equilibrium is established the subsequent changes accompanying increase of grade belong to the category considered in the previous section.

---

[12] Turner, F. J.: The Metamorphic and Intrusive Rocks of Southern Westland, Trans. N. Z. Inst., 63, pp. 176-284, 1933.

[13] Op. cit., p. 57.

[14] Tilley, C. E.: On Garnet in Pelitic Contact-zones, Min. Mag., 21, pp. 47-50, 1926.

A few typical examples of metamorphism by adjustment to decreased temperature are given below:

(1) In the transition from acid igneous rock to quartz-sericite-schist by dynamic metamorphism at low temperature, the main mineralogical changes are sericitisation of orthoclase and chloritisation of biotite. Sericitisation, however, by no means invariably accompanies crushing and mylonitisation, even though the transition from biotite to chlorite may be complete.[15] Doubtless the quantity of available water is the main factor that determines whether the reconstituted assemblage will be quartz-sericite-chlorite or quartz-microcline-chlorite, and both must therefore be regarded as equilibrium assemblages under conditions of high stress and low temperature.

(2) Low-grade dynamothermal metamorphism of basic igneous rocks (or of sediments directly derived from these) produces green schists of several types, the origin of which has recently been partially discussed by the writer.[16] The following alternative courses of metamorphism are known:

(a) Vogt[17] has described the sequence

Pyroxene-labradorite.
↓
Hornblende-labradorite.
↓
Hornblende-oligoclase-epidote-quartz.
↓
Actinolite-albite-epidote-chlorite-quartz.
↓
Albite-epidote-chlorite-quartz.
↓
Albite-chlorite-quartz.

---

[15] Cf. Wiseman, J. D. H.: A Contribution to the Petrology of the Metamorphic Rocks of East Greenland, Q. J. G. S., **88**, pp. 312-349, 1932.

[16] Turner, F. J.: The Genesis of Oligoclase in Certain Schists, Geol. Mag., **70**, pp. 529-541, 1933.

[17] Op. cit.

The last two stages involve progressive removal of lime although apparently dependent upon further decrease in temperature below that which governed crystallisation of the actinolitic schists.

(b) Eskola[18] has noted in certain Fennoscandian schists a generally similar sequence of mineralogical changes to that described by Vogt, except that the final stage of metamorphism involves the change

Actinolite-epidote-albite.
↓
Albite-epidote-chlorite-calcite.

(c) In the schists of Central and Western Otago, New Zealand, the writer has frequently observed the change

augite-hornblende-plagioclase
↓
actinolite-albite-epidote-chlorite,

even at the lowest possible grades of dynamothermal metamorphism, where intercalated pelitic sediments have recrystallised as slates and phyllites. This is not an isolated phenomenon but has been observed in a large number of rocks from widely scattered localities, and the assemblage actinolite-albite-epidote-chlorite is therefore considered to constitute a true equilibrium association under these conditions.

I have therefore suggested that the formation at low grades of albite-chlorite-epidote-schists and albite-chlorite-schists as described by Vogt, is only possible in the presence of sufficient water, and under conditions which allow (as recognised by Vogt) continuous removal of lime from the system. Again the crystallisation of albite-epidote-chlorite-calcite schists must be conditional upon the presence of sufficient CO_2 to combine with the lime set free in chloritisation of actinolite. When neither of these conditions holds, the assemblage actinolite-albite-epidote-chlorite remains stable even at the lowest temperatures.

When this suggestion was previously put forward by the writer, he was unaware that Eskola[19] had long previously formulated the problem of the possible relationships of these mineral assemblages, and had reached a conclusion which appears to be in general accordance with the scheme outlined above.

(3) The case of hydrothermal metamorphism of picrites and peridotites with the ultimate production of talc-carbonate rocks as recently described by Hess[20] is instructive. The changes with fall-

---

[18] Op. cit., pp. 73-77, 1925.
[19] Op. cit., pp. 77, 78, 1925.
[20] Op. cit.

ing temperature and approximately constant low stress are

Olivine-pyroxene-plagioclase (minor).
↓
Hornblende.
↓
Actinolite-chlorite.
↓
Chlorite-magnetite.
↓
Talc-carbonate-magnetite.

From the examples given above it will be seen that water plays a much more important part in metamorphism of the type under consideration than in metamorphism by adjustment to rising temperature. Apart from its general function in facilitating reconstitution (which applies to metamorphism of all kinds), it renders possible the crystallisation of low-grade hydroxyl-bearing minerals such as sericite, chlorites, talc, actinolite, and epidote. Furthermore, in some cases it even brings about changes in bulk composition by progressive removal of bases such as CaO and Al_2O_3 from the metamorphosed rock. In special but well-known instances, the presence of CO_2, acting in conjunction with water, has an important influence in determining the nature of equilibrium assemblages crystallising at low grades.

Though most writers do not include transformations involving marked change in bulk composition under the heading of metamorphism, such cases as those referred to above cannot well be excluded. Sharp distinction between changes involving addition or elimination of water only, and those accompanied by removal of certain bases or addition of CO_2 is hardly practicable, since some of the most widely distributed and best known metamorphic rocks owe their origin to reactions of this latter type.

A MODIFIED CONCEPTION OF MINERAL FACIES APPLIED TO GREEN SCHISTS.

It is suggested that application of the following principles may lead to a better understanding of the significance of mineral facies in metamorphic rocks:

(1) The nature of an equilibrium assemblage of minerals crystallising in a metamorphic rock of given chemical composi-

tion is determined mainly by temperature and stress. This is true more especially at medium and high grades of metamorphism; under such conditions the same equilibrium assemblage is usually developed for a given range of temperature and stress whether reconstitution of the rock is in response to rising or falling temperature, for in the latter case sufficient water is usually present to allow crystallisation of such hydroxyl-bearing minerals (e.g. amphiboles and micas) as are stable at these grades.

(2) With metamorphism at low grade, and particularly when readjustment of equilibrium is governed by falling temperature, the nature of the equilibrium assemblage for a given bulk composition is influenced by the amount of water available, the presence or absence of CO_2 and the extent to which removal of certain bases (e.g. CaO and Al_2O_3) is possible. Several distinct low-grade facies may therefore be recognised, and some of these have already been defined by previous writers such as T. Vogt and H. H. Hess. As an example of the application of this modified conception of mineral facies, an outline is given of the various equilibrium assemblages produced by low-grade regional metamorphism of basic igneous rocks or their altered equivalents. This group of rocks not only shows the development of a number of distinct mineral assemblages within the same range of temperature and stress, but also illustrates well the necessity for determining further chemical and petrographical data (for example with reference to the varieties of amphibole and chlorite involved). Until more complete evidence of this type is available no final conclusion can be reached, but the scheme outlined below is put forward tentatively as a summary and explanation of the facts at present known.

(1) The transition ***pyroxene** (or hornblende)-**plagioclase** → **actinolite-epidote-albite-minor chlorite*** takes place under more than one set of conditions. According to Vogt[21] the essential controlling factor is temperature, provided that sufficient water is present to allow formation of the hydroxyl-bearing minerals concerned; and judging from his correlation of the actinolite-greenschist facies with the almandine-schist facies as defined for quartzo-feldspathic sediments, he considers that the temperature at which crystallisation of actinolite occurs is relatively high. In a recent paper Hess[22] has advanced similar

---

[21] Op. cit., pp. 407-410, 515, 516.
[22] Op. cit., pp. 405-407.

conclusions, and especially stresses the idea that the formation of actinolite-schists of this type is often due to purely hydrothermal metamorphism, the influence of stress being negligible. In other well-known instances, however (cf. Eskola[23] and Sugi[24]), the formation of actinolite-albite-epidote-chlorite-schists is considered to be the result of dynamothermal metamorphism of fairly low grade involving high stress. Earlier in this paper the writer has recorded his view that the same assemblage of minerals may be formed under conditions of high stress and relatively low temperature (corresponding to the lowest grade of metamorphism within the Chlorite Zone of associated pelitic schists), provided that CO_2 is absent and that removal of lime is not possible (perhaps a result of insufficient water being present).

It should be noted that while in some instances the optical properties of the actinolite indicate that it is a normal non-aluminous variety (e.g. in the actinolitic rocks described by Sugi and by Hess), an aluminous actinolite or actinolitic hornblende is the characteristic mineral of many "actinolite"-schists. Eskola[25] has further shown that both birefringence and refractive indices are often considerably lower in these relatively aluminous actinolites than in the better known members of the actinolite and hornblende series. More data are needed on this point however, for Kunitz[26] has recorded an aluminous actinolite from New Hampshire, which is closely similar chemically to Eskola's "actinolitic hornblende", but which has optical properties appropriate to the normal actinolite series. Theoretical considerations favour non-aluminous rather than aluminous actinolite as the stable amphibole in these schists, since as shown by Vogt,[27] the essential transformation at this stage is *aluminous hornblende→actinolite-chlorite-epidote*. The presence of aluminous actinolites may possibly be due to incomplete attainment of equilibrium, or perhaps to lack of sufficient water to allow complete chloritisation.

(2). The transition *actinolite-chlorite-epidote-albite→chlor-*

---

[23] Op. cit., 1925.

[24] Sugi, K.: On the Metamorphic Facies of the Misaka Series in the Vicinity of Nakagawa, Prov. Sagami, Jap. Jour. Geol. and Geogr., **9**, pp. 87-142, 1931.

[25] Op. cit., pp. 41-44, 1925.

[26] Kunitz, W.: Die Isomorphieverhältnisse in der Hornblendegruppe, Neues Jahrbuch, **60**, A, pp. 193, 194, 244, 1930.

[27] Op. cit., pp. 408, 409.

ite-epidote-albite has been recorded by many writers, most of whom believe that the reaction takes place only at a lower temperature than that required for conversion of hornblende to actinolite, chlorite, and epidote. Vogt has stressed the fact that this transition involves not only further addition of water, but progressive removal of CaO from the system, presumably by a process of metamorphic diffusion under the influence of plentiful water. Thus the association chlorite-epidote-albite, once formed, would appear to be capable of persisting in a state of internal equilibrium beyond the range of temperatures at which it originated, if subjected to increasing temperature. Ultimately under conditions corresponding to the Biotite or Almandine Zones as defined for pelitic schists, the chlorite-epidote-albite association would give rise, if the writer's views are correct, to green hornblende + plagioclase.

(3) The transition *actinolite-chlorite-epidote-albite* → *chlorite-epidote-albite-calcite* takes place in the presence of CO_2 and water during dynamic or dynamothermal metamorphism of the lowest grade. Since no noteworthy change in the relative proportions of the more important bases is involved, the reaction is reversible: subsequent increase of temperature, as in a later phase of progressive metamorphism, will therefore cause crystallisation of amphibole at the expense of chlorite and calcite.[28]

In certain instances (e.g. in the green schists of the Start area of Devon[29]), schists consisting of pale aluminous hornblende (actinolitic hornblende), epidote, and albite-oligoclase or acid oligoclase appear to the writer to have arisen thus by reaction between chlorite and calcite at a relatively advanced grade, still corresponding, however, to part of the Chlorite Zone of pelites. It is possible, and indeed is theoretically expectable, that the association actinolite-epidote-chlorite-albite should also be formed by the transition *chlorite* + *calcite* → *actinolite* (*non-aluminous*) + *epidote*. It is therefore difficult to explain why, in some instances at any rate, actinolitic hornblende + anorthite should be produced at low grades in preference to non-aluminous actinolite + epidote. Since the reaction takes place with rising temperature and elimination of CO_2, the explanation may possibly lie in the fact that progressive removal of water from the system has favoured the crystallisation of the least hydrous assemblage possible. Until further data are available it would be unprofitable to generalise further.

---

[28] Turner, F. J.: op. cit., Geol. Mag., 1933.

[29] Tilley, C. E.: Petrology of the Metamorphosed Rocks of the Start Area, Q. J. G. S., 79, pp. 172-204, 1923.

In the above discussion possible variation in the composition of chlorites has not been taken into account, though actually there appears to be considerable diversity among the chlorites of green schists formed under various conditions. Again minerals of the stilpnomelane group sometimes partly or completely take the place of chlorite in such rocks,[80] though the conditions favouring their crystallisation are not yet fully understood. It is obvious therefore that, when sufficient data have been recorded, the exact chemical nature of minerals such as chlorite or stilpnomelane present in these schists will have to be taken into account in defining and recognising equilibrium assemblages.

In applying the facies principle to green schists it has been customary to recognise two facies corresponding to low grades of metamorphism within the Chlorite Zone as defined for pelites. These facies, in order of increasing grade, are based on the assemblages

(a) chlorite-albite-epidote and
(b) pale (actinolitic) hornblende-oligoclase-epidote (Tilley[81]),
or actinolite-albite-epidote-chlorite (Vogt,[82] Sugi[83]),
or actinolitic hornblende-albite-epidote (Eskola[84]).

In the above scheme the facies are founded upon variations in mineral composition dependent upon temperature and stress alone. If, however, account is also taken of the function of water and CO_2 in metamorphism, and of the conditions under which the assemblages originate, rather than those under which any assemblage once formed may subsequently remain in a state of equilibrium, several facies corresponding to different grades within the Chlorite Zone may be recognised:

(1) A facies corresponding to a relatively high grade of metamorphism, and independent of the presence or absence of CO_2, or of the amount of water available in excess of a minimum requirement. To this facies belong the majority of those schists which consist of *actinolite or actinolitic horn-*

---

[80] Turner, F. J.: Schists from the Forbes Range and Adjacent Country, Western Otago, Trans. Roy. Soc. N. Z., **64**, pt. 2, 1934.

[81] Op. cit., p. 1699, 1924.

[82] Op. cit., pp. 407-410, 523.

[83] Op. cit., p. 134.

[84] Op. cit., p. 75, 1925.

blende, albite epidote and minor chlorite, irrespectively of whether their crystallisation was governed by increased or decreased temperature. Since, however, the same set of minerals may form at a distinctly lower grade under quite a different set of conditions, the facies under consideration cannot appropriately be named after this assemblage of minerals.

The relatively rare association *actinolitic hornblende-oligoclase-epidote* has not yet been recorded, as far as the writer is aware, except in rocks that appear to have crystallised under the conditions requisite for this facies, and the writer[85] has therefore followed Tilley in naming the facies after this assemblage. It has already been stated in this paper, however, that the oligoclase-bearing assemblage may actually be either in a state of internal disequilibrium at this grade, or else the product of a special type of metamorphism in response to rising temperature. For these reasons it might be preferable to drop the term Pale hornblende-oligoclase-epidote-schist Facies altogether, or else to retain it only tentatively. If the former course were adopted, no name would at present be available for the facies, though some such mineralogical changes as the appearance of green biotite in potassic green schists, or even changes in composition of epidotes and chlorites in schists of this group, might at some future date be used in this connection, when such transformations and the conditions that govern them are more fully understood.

(2) Several distinct facies, all corresponding to the lowest grade of metamorphism within the Zone of Chlorite, may be recognised:

(a) During crystallisation CO_2 is absent and water is insufficient to allow chloritisation of actinolite. To the facies that corresponds to these conditions belong certain low-grade *actinolite-albite-epidote-chlorite-schists* such as those recorded from Western Otago, New Zealand, by the present writer.[86] Here, too, though the facies itself may be recognised, a distinctive mineral assemblage after which it may appropriately be named has yet to be defined.

(b) During crystallisation CO_2 is active and water is sufficiently plentiful to allow crystallisation of the characteristic assemblage *chlorite-albite-epidote-calcite,* after which the facies may be named. This is one of the most clearly defined of low-grade facies, in that the characteristic assemblage of minerals crystallises only within a limited range of temperature, and furthermore is readily transformed at higher temperatures (if the writer's interpretation of the evidence is correct) into an association containing actinolitic amphibole which is formed by reaction between chlorite and calcite.

---

[85] Op. cit., Geol. Mag., p. 538, 1933.
[86] Op. cit., 1934.

It is probable as suggested by Eskola[87] that the *talc-carbonate-schists* belong approximately to this facies, though the observations of Hess upon the origin of soapstones appear to throw some doubt upon the exactness of this correlation.

(c) Crystallisation takes place in the absence of CO_2, but sufficient water is present to bring about chloritisation of actinolite, a process which involves progressive removal of lime from the rock. In green schists the resultant assemblage is *chlorite-albite-epidote* and a Chlorite-albite-epidote-schist Facies (= Eskola's Greenschist Facies) may be recognised on this basis.

(d) According to Vogt, crystallisation in the absence of CO_2 and in the presence of abundant water sometimes involves removal of other bases than lime (notably alumina) from the system. The resulting rock in the green-schist series is a *chlorite-albite-schist*, and Vogt has based a Chlorite-albite-schist Facies on this association. Possibly this extreme type of alteration takes place at temperatures even lower than those which control crystallisation of rocks of the preceding facies.

UNIVERSITY OF OTAGO,
DUNEDIN,
NEW ZEALAND.

---

[87] Op. cit., p. 54, 1925.

LAYERED PERIDOTITIC LACCOLITHS OF THE TROUT RIVER AREA, NEWFOUNDLAND.

EARL INGERSON.

ABSTRACT.

The Trout River Area, which lies between the Bay of Islands and Bonne Bay on the west coast of Newfoundland, contains two peridotitic intrusions, a gabbroic intrusion, and andesite and basalt tuffs, breccias, and flows which, with the intercalated shales and sandstones of Upper Ordovician age, form the framework of the intrusive masses.

The peridotitic intrusions are remarkably layered laccoliths that have been tilted (33° and 45°) to the northwest, peneplaned, uplifted, and partly dissected. In each there is a basal zone of dunite and bronzite peridotite, 14,400 feet thick in one laccolith and 10,300 feet thick in the other, which is overlain by a Critical Zone, 7150 feet thick in one laccolith and 6200 feet thick in the other, consisting of alternating layers of feldspar-rich and olivine-rich rocks ranging from 8 to 3800 feet thick. Above the Critical Zone is another zone of dunite and peridotite, which is like the basal zone, but only one-tenth as thick.

Crystal settling probably accounts for the formation of the thick basal layers and for the fact that the layers of the Critical Zones are parallel to the floors. The hypothesis is proposed that the origin of the recurrent layers composed of the same minerals must be connected with phenomena outside of the magma chamber. Periodic enrichment of the rest-magma in the constituents of the early-formed minerals, possibly aided by re-solution of parts of the border facies, is postulated.

Location of area.—The area between the Bay of Islands and Bonne Bay, called the Trout River Area from the stream that flows through it from southeast to northwest, forms a distinct geologic as well as physiographic province of western Newfoundland. The area is a compact unit of elliptical shape. Fig. 1 shows its location with respect to the island.

Stratigraphy and structure.—A recent memoir by Schuchert and Dunbar (5)[1] gives a detailed account of the stratigraphy of western Newfoundland and tells what is known of the structure of that part of the island. All of the sedimentary rocks of the Trout River area are shales (mostly slaty) and sandstones that in all probability belong to the Humber Arm series.

---

[1] Numbers in parentheses refer to the bibliography at the end of the paper.

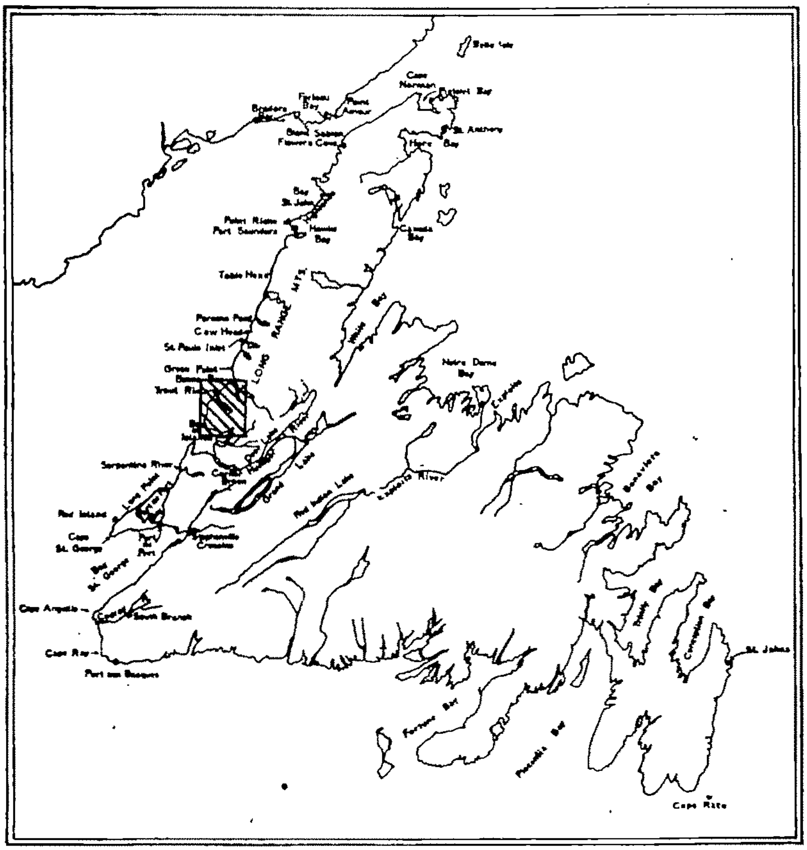


Fig. 1. Index map showing the location of the Trout River area.

Schuchert and Dunbar classify this series as Middle and Upper Ordovician and suggest that the uppermost part of it may be Silurian. As its age is not definitely known, it is herein referred to as Upper Ordovician, because part of it almost certainly represents Upper Ordovician time, and its upper and lower limits are unknown.

Considerable thicknesses of volcanic rocks are interbedded with the Humber Arm series of the area. They range from trachytic to basaltic, but most of them are andesitic. They occur as pyroclastic beds—tuff, breccia, and agglomerate—and as flows, both massive (but amygdaloidal) and pillow lavas.

The sedimentary and extrusive rocks generally strike northeast-southwest, except where they have been pushed aside by the intrusions. They dip uniformly to the northwest, except in some places northwest of the intrusive masses, where the dip is reversed. The contacts between the intrusive and sedimentary rocks show the same strike; the dip of the contacts at the southeastern sides of the intrusions is to the northwest, but that of the northwestern contacts is to the southeast.

THE INTRUSIONS.

Description.—The two laccolithic masses that were studied in detail correspond to Table Mountain and North Arm Mountain. Fig. 2 shows the approximate distribution of the rocks of the Trout River area and also the physiographic divisions. The surrounding sedimentary and extrusive rocks have been worn down, leaving the intrusive bodies wonderfully well exposed.

Table Mountain is an almost rectangular mass 7¾ miles long and 5¼ miles wide. Its length is parallel to Trout River Gorge, which strikes N 45° W. All of the sides of the mountain except the northwest are practically straight. Most of the mountain is composed of bare yellow-weathering rock, but for 3 miles its northwestern extremity is banded with varicolored rocks and is covered with brush.

The North Arm Mountain mass is much like the other one except that it is elliptical rather than rectangular in shape. It is 8¾ miles long by 5¾ miles wide and its longer axis is almost at right angles to that of Table Mountain. The northwest part of it is banded and is covered with brush.

Nature of the intrusions.—The relations observed in these bodies might lead one to suspect that they are chonoliths. Daly defines a chonolith as "a discordant igneous body (a) injected into dislocated rock of any kind, stratified or not; (b) of shape and relations irregular in the sense that they are not those of a dike, sheet, laccolith, bysmalith, ethmolith, sole injection, or neck; and (c) composed of magma passively

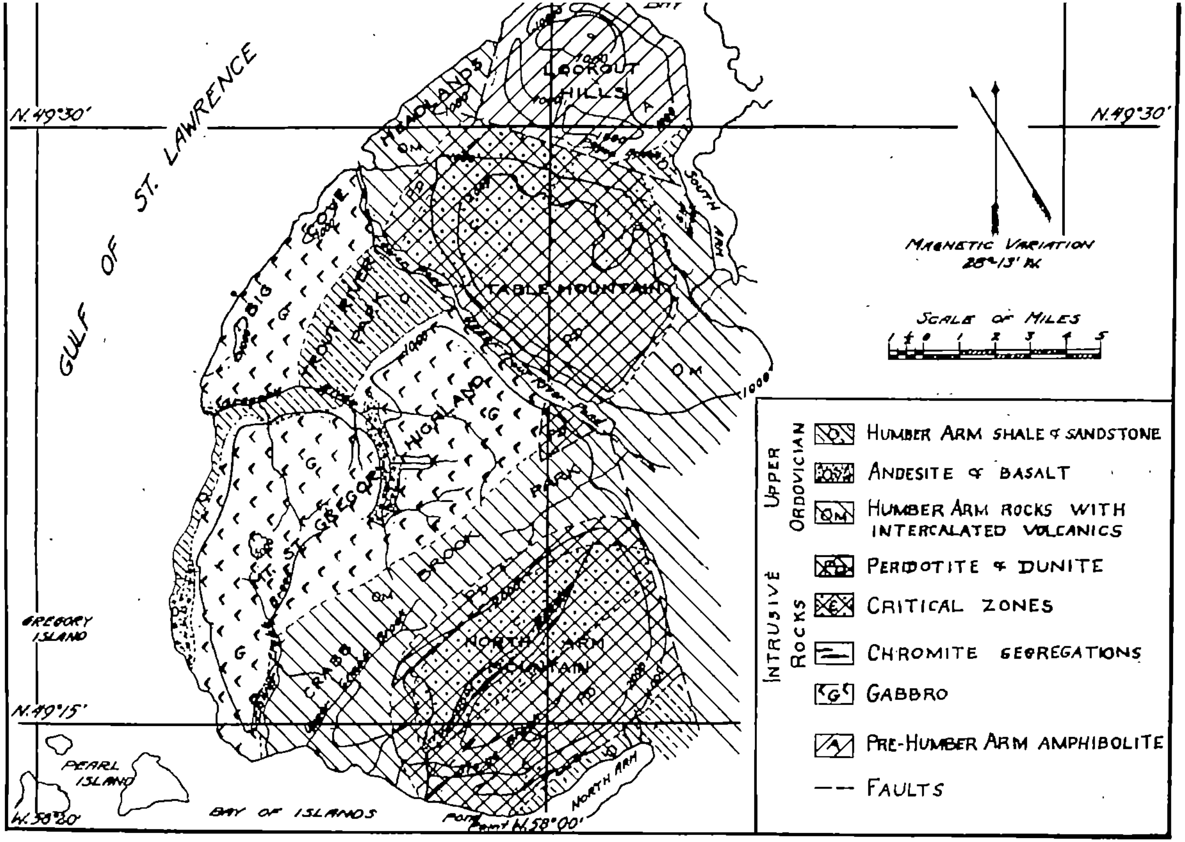


Fig. 2. Geology of the Trout River area. Contour interval 1000′.

squeezed into a subterranean orogenic chamber or actively forcing apart the country rocks" (1, p. 106).

A section like the ones that he shows on page 107 might explain the moderate dip of the floors (southeastern contacts of the intrusive masses) and the steep reverse dip of the contacts away from the floors. However, a chonolith is by definition a discordant and irregular body. The contacts of the intrusive bodies under consideration are, wherever seen, parallel to the stratification of the enclosing rocks. The masses are, moreover, regular in shape and cannot, therefore, be called chonoliths.

Floors.—The floor is always a critical factor in the interpretation of the character of any intrusive body. Before a positive classification of such a mass can be made it is necessary to determine (1) whether it is concordant or discordant, (2) whether it has a floor, and (3) the nature of the floor, whether it is essentially a plane or is basin-like.

Lopoliths or laccoliths?—As the intrusive bodies under consideration are generally concordant and have definite floors the question of their interpretation is narrowed down to whether they are lopoliths or laccoliths. The nature of the floor and roof is the critical point in distinguishing between these types of intrusive bodies. The floor of the North Arm Mountain mass is remarkably well exposed and is everywhere fairly close to salt water so that it is relatively accessible. The contact was followed for more than 5 miles and dip and strike readings were taken at intervals over this distance. All of the readings agreed within a few degrees, showing that the floor is essentially a plane and does not curve around the mass. Fewer measurements were made of the floor of the other body, but those taken indicate the same general relation for the Table Mountain mass. This relation favors the interpretation that the intrusions are laccoliths rather than lopoliths, because the strike of the floor of a lopolith should change progressively so as to "box the compass."

The rocks of both of these igneous bodies are layered to a striking degree. If differentiation was gravity controlled in them, then the arrangement of the layers in the two types of intrusive bodies under consideration should be distinctive. In a lopolith the basal layers would form parallel to the floor and thus would themselves be basin-shaped. There should be an upper border facies with essentially the same composition as the basal part. If gravity separation is effective, then the lower ultrabasic border should be thicker than the similar zone at the top.

The differentiated layers in the central part of the mass (the Critical Zone[2]) should also be parallel to the floor, because, although crystals can probably sink through the magma under the direct influence of gravity, it is extremely unlikely that they could migrate down the slope of the floor through the viscous magma to collect at the bottom of the basin, like shot in a round-bottomed flask of water. The upper zone should be parallel to the roof, which in described lopoliths is basin-shaped, though less sharply concave than the floor.

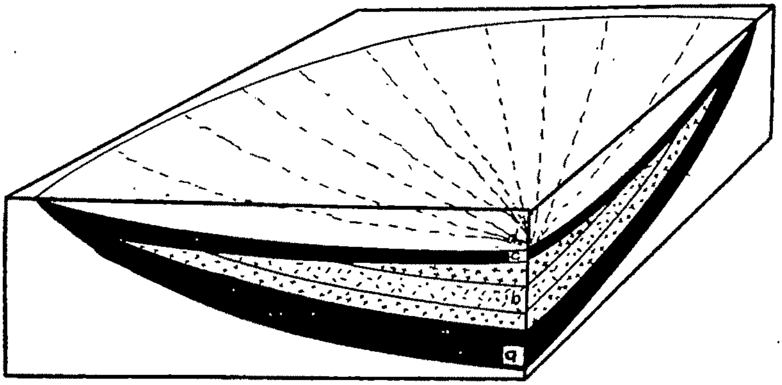


Fig. 3. Idealized form of a differentiated lopolith; a, basal zone; b, critical zone; c, upper border facies; d, roof.

Fig. 3 shows an idealized diagram of a differentiated lopolith. In such a body not only the floor, but also the layers of the critical zone, would box the compass. The outcrops of these layers would be closed concentric curves in an ideal untilted lopolith. The floor would everywhere dip under the igneous rock.

If such an intrusive body were tilted and eroded, then the roof and the floor would form the outside contacts of the intrusion, rather than the floor on all sides. The contacts would dip in the *same* direction, in contrast to the case of the untilted lopolith. The different layers, instead of boxing the compass, would form cresentic outcrops, the exact shape of which would depend upon the original dip of the layers and the amount of tilting. These relations are illustrated in Fig. 4.

---

[2] Critical Zone is a term coined by Hall in 1926 (3). As a descriptive term he used it for the part of the Bushveld Complex that Wagner called the Differentiated Series. It is also a genetic term: Hall intended it to imply the critical adjustment of physico-chemical conditions that must have obtained at the time of the formation of such a recurrent series of igneous rocks.

In a differentiated laccolith the arrangement would be different. The thick basal zone and the critical zone would be parallel to a plane floor and the thinner zone at the top would be parallel to an arched roof. These relations are indicated in Fig. 5.

The application of these criteria to actual cases is not always easy, because in intrusive bodies that have not been tilted nor deeply eroded the basal layers may not be accessible. However, the masses under consideration are peculiarly adapted for study. In both of them the thick basal layers, as well as the thinner ones of the critical zones, are essentially parallel to the floors.

The upper (NW) contact of the North Arm Mountain mass is so covered with scrub spruce that its study was found to be impracticable, if not impossible. However, there is a canyon cutting across the upper part of the Table Mountain mass almost at right angles to the contact with the roof, and the actual contact was found at that place. An ultrabasic border almost identical in composition with the basal part of the intrusion, but only one-tenth as thick, occurs adjacent to the roof. The roof dips under the intrusive rock at a high angle, as would be expected of a tilted, bun-shaped mass. Fig. 6 is an idealized diagram showing these relations.

From the evidence presented it is manifest that the intrusions must be interpreted as laccoliths. The remarkable uniformity in dip and strike of the floors over long distances makes that interpretation unavoidable. The laccoliths have been tilted to the northwest, peneplaned, elevated, and the weaker rocks have been worn from around their edges.

Age of the laccoliths.—The intrusions of the west coast of Newfoundland have commonly been considered to be of Devonian age, although no definite determination can be made from stratigraphic evidence. The inference rests in part on the fact that the Silurian of the Exploits Valley region is cut by intrusions which Murray and Howley believe to be of the same age as those of the west coast.

On Red Island there are continental beds that are probably

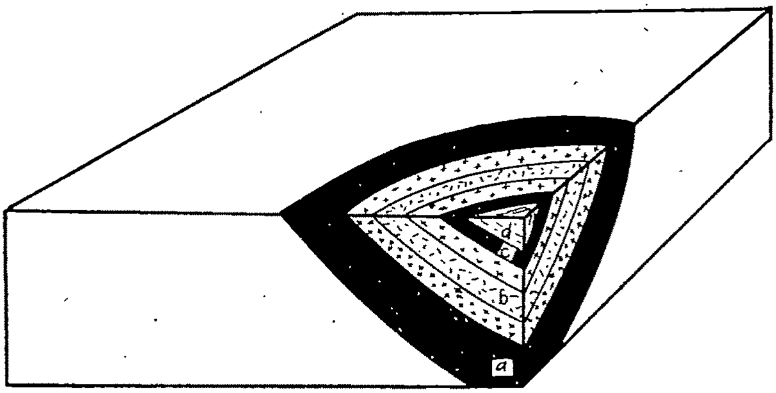


Fig. 4. Idealized diagram of a lopolith like that shown in Fig. 3, after it has been tilted and peneplaned.

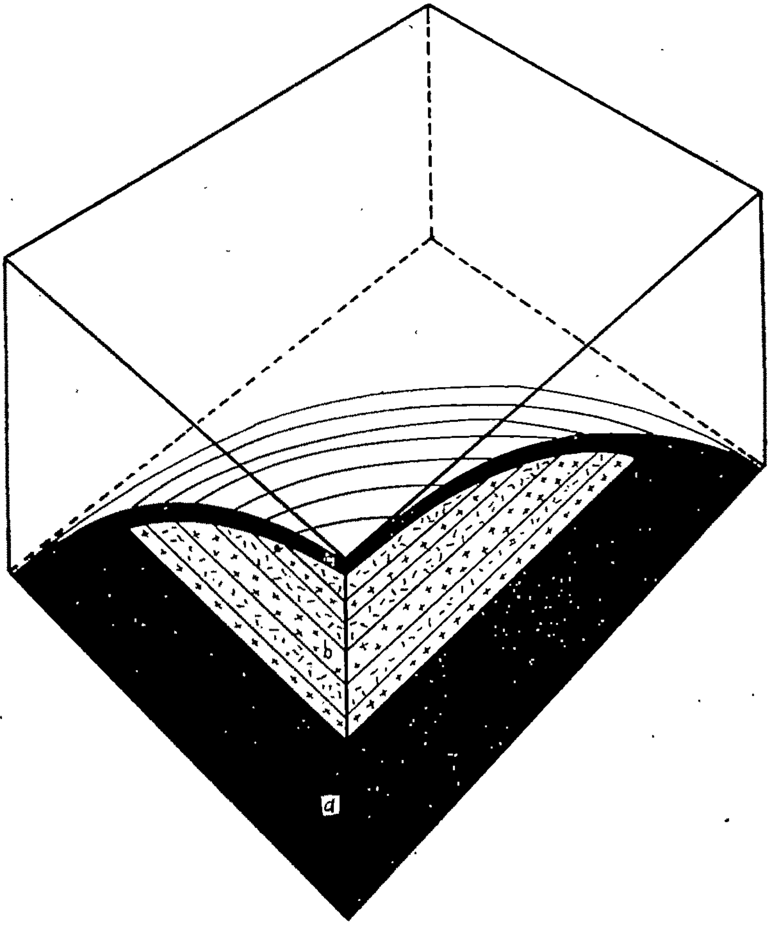


Fig. 5. Idealized form of a differentiated laccolith with steep sides; a

of Mississippian age, which contain boulders of porphyritic igneous rocks. Red Island is off the west coast of St. George Peninsula, not over 30 miles from the igneous rocks of the Lewis Hills, which are part of a massif south of the Bay of Islands like the one of the Trout River area. The conglomerates of the Lower Devonian on the shore of the peninsula, between Red Island and the Lewis Hills, are not known to contain any boulders of such igneous rocks, or any like those of the Lewis Hills. If the beds on Red Island are Mississippian, the relations described above indicate that the igneous rocks may have been formed after Lower Devonian and before Mississippian time.

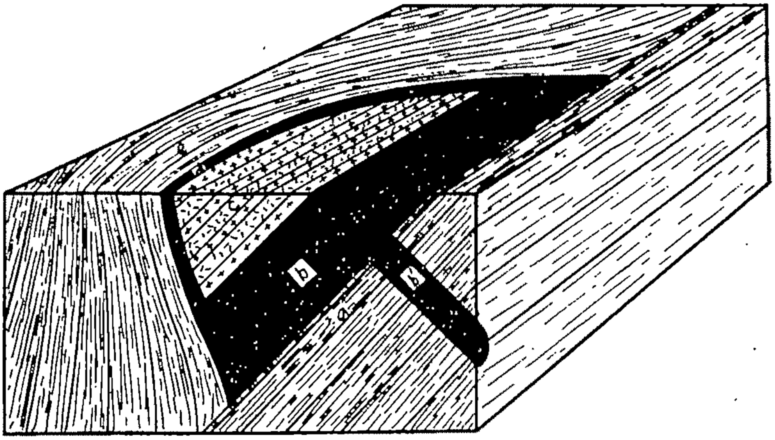


Fig. 6. Idealized diagram of a laccolith like that shown in Fig. 5, after it has been tilted and peneplaned; a, sedimentary floor; b, basal zone; b', conduit; c, critical zone; d, upper border facies; e, roof.

It is quite possible, however, that these are older igneous rocks that were not exposed to erosion until the beginning of the Mississippian, following the uplift brought about by the Acadian disturbance. The igneous rocks in the conglomerates on Red Island have laths of feldspar up to a quarter of an inch in length in an aphanitic groundmass. No similar rocks have been found in place anywhere along the west coast. These rocks contain phenocrysts of quartz, and so may be entirely unrelated to the igneous activity that produced the ultrabasic intrusions of the west coast.

Banding.—There is a remarkable zone of banding in each intrusion. In walking across North Arm Mountain from North Arm one encounters the banding just before the canyon of Liverpool Brook is reached. The bands range in width from eleven feet to one mile. Practically all of the narrow bands are southeast of Liverpool Brook. The zone is of striking appearance; where it outcrops on a bare rise it gives the impression of sedimentary strata, contrasting sharply with the homogeneous yellow rock southeast of it. The contrast is heightened by the greater amount of brush on the banded zone. The banding is regular and can be traced entirely across the flat top of North Arm Mountain; its strike is parallel to the strike of the southeastern contact of the igneous rock.

The different rocks of the banded zone have about the same resistance to erosion, so that the different layers do not project and recede sharply, as do the strata of a sedimentary series. However, some of the layers are slightly less resistant to erosion than others and these have been worn into swales parallel to the banding; the more resistant layers form low intervening ridges. Exceptionally the contacts between unlike layers are sufficiently well exposed so that the dip of the layers can be approximately determined. It closely parallels that of the floor.

The banded zone of Table Mountain is much like that of North Arm Mountain. It extends from Lower Trout River Pond to the escarpment overlooking Payne Valley. In appearance, coloring, topographic expression, vegetation, and relation to the floor it closely resembles the similar zone on North Arm Mountain. The bands are wider and less numerous on Table Mountain.

Petrography of the laccoliths.—The banding has been described in a general way and there remains to give the petrographic character and thicknesses of the individual layers, and to attempt an explanation of how the layering was produced. The accompanying tables show the sequences and thicknesses of the individual layers. The top of the table corresponds to the top of the laccolith in each case. The igneous rock classification used is essentially that of Niggli (4).

TABLE I.

Differentiates in the Table Mountain Laccolith.

Layer No.	Thickness (in feet)		Character	Specific Gravity
	300	Upper Border Facies	Dunite[3]	2.56
	1200		Bronzite peridotite (saxonite)	2.69
14	350	Critical Zone	Olivine gabbro (without augite)	2.77
13a	3350		Leuco-gabbro-anorthosite zone	2.77
13	50		Gabbro	2.86
12	80		Bytownite dunite	2.77
11	100		Anorthositic gabbro	2.77
10	110		Bytownite peridotite	2.84
9	175		Leuco-gabbro	2.79
8	100		Bytownite-bearing dunite	2.80
7	80		Anorthosite	2.76
6	80		Bytownite peridotite	2.77
5	950		Leuco-gabbro	2.92
4	125		Bytownite peridotite	2.86
3	1300		Leuco-gabbro	2.93
2	80		Olivine mela-gabbro	2.94
1	220		Olivine-bearing augitite	3.34
	4000	Basal Zone	Bronzite dunite	2.87
	10000		Bronzite peridotite	2.72
	400		Bronzite dunite	2.67

[3] Dunite = 90+% olivine.

In the basal zones of the intrusions there are numerous segregations of bronzite, some of which are as much as two feet thick and tens of feet long. Some of the thinner layers of bronzite have been sharply folded.

There is one lens of chromite in the basal zone of the North Arm Mountain laccolith that may eventually prove to be a commercial source of chromium.[4] The deposit outcrops for more than a quarter of a mile near the northwest brink of the canyon of Stone Brook about two miles above its mouth. The strike is parallel to that of the floor. The lens averages some five feet in thickness, but much of the material is dunite separating relatively small lenses of chromite. The segregation is in the upper dunite layer of the basal zone.

It is possible that there is a similar deposit in the basal zone of the Table Mountain laccolith, but none has been reported. If such a deposit had ever been formed, it is also possible that it has not been exposed by erosion, or that it has been separated from the main mass by faulting. Both ends of the

---

[4] Snelgrove, A. K.: personal communication.

TABLE II.

Differentiates in the North Arm Mountain Laccolith.

Layer No.	Thickness (in feet)		Character	Specific Gravity[*]
	?	Upper Border Facies	Probably an olivine-rich rock	?
21	950+	Critical Zone	Leuco-gabbro	2.92
20	100		Olivine gabbro (without augite)	2.89
19	3800		Gabbro-anorthosite	2.92
18	30		Bronzite olivine-rich augitite	3.17
17a	40		Leuco-gabbro	2.95
17	50		Olivine gabbro	3.23
16	40		Bronzite-olivine augitite	3.24
15	50		Leuco-gabbro	2.98
14	15		Bronzite-bearing augitite	3.27
13	20		Augite olivine-rich bronzitite	3.03
12	60		Dunite	2.64
11	100		Bytownite-bronzite augitite	3.24
10	70		Olivine augitite-bronzitite	3.17
9	90		Gabbro	3.03
8	10		Augite olivine-rich bronzitite	2.97
7	8		Leuco-gabbro	2.94
6	20		Augite olivine-rich bronzitite	2.86
5	25		Gabbro	2.87
4	25		Augite-bearing olivine bronzitite	2.97
3	150		Bronzite-augite peridotite	3.00
2	350		Gabbro	2.97
1	210		Olivine-bearing bronzite augitite	3.26
	3750	Basal Zone	Dunite (Chromite segregations)	2.68
	5250		Bronzite peridotite	2.67
	300		Dunite (Some chromite)	2.67
	700		Bronzite peridotite	2.67
	300		Dunite	2.66

[*] The specific gravity of these rocks is more a function of the degree of alteration than of original mineral composition, so these values do not have much meaning in a discussion of differentiation.

Table Mountain body have been down-faulted so deeply that only a small part of one of them now outcrops.

Alteration.—The basal zones and upper border facies are intensely serpentinized (80%±), as are the olivine-rich rocks of the critical zones. The alteration appears to be controlled more by mineral composition than by any other single factor, as most of the feldspar-rich layers are but slightly altered. The nature and intensity of the alteration are influenced considerably by the proximity of faults even in the feldspar-rich rocks.

Hypothesis of origin of the layering.—The layering must have been produced by differentiation in place because:

(1) The rocks are altered normal igneous rocks with no trace of any texture characteristic of metamorphic rocks.

(2) The banding is on too large a scale to be the result of metamorphic processes, some of the layers being thousands of feet thick.

(3) The layering is definitely related to the floors of the intrusions and is probably unrelated to any regional stresses that might have caused metamorphism.

(4) There are no chill zones nor sharp contacts between adjacent layers, one or both of which would be present if the layering had been produced by successive injections of magmas of different compositions.

(5) Experimental evidence indicates that "heterogeneous magmas" probably never exist.

If layering in igneous masses is produced by differentiation and differentiation is in turn controlled by crystallization, then there appears to be but one probable fundamental cause of repetitions of layers of the same mineral composition. This cause is recurrent enrichment of the restmagma in the constituents of the early-formed minerals (Mg, Cr, and Fe in the Trout River laccoliths). This enrichment might be brought about in either, or both, of two different ways: (1) By recurrent intrusions of magma of the original composition, or (2) by re-solution of parts of the border facies after extrusion of some of the gas-rich upper part of the restmagma.

Perhaps the simplest way to present the writer's conception of how these layered intrusive bodies formed is to outline the sequence of events as he pictures them. In the following outline, which has been devised with special reference to the Table Mountain mass, it is assumed that the magma was essentially fluid at the time of intrusion; that few or no crystals had already formed in it. This assumption is supported by the fact that the intrusive rock at the immediate contact with the country rock appears to have been very fine-grained. The rock at the contacts is completely serpentinized, so that it is not possible to estimate the grain size as accurately as can be done where there are remnants of olivine grains. However, the mesh structure of the serpentine gives an indication of the order of magnitude of the original grain size. If there were any crystals in the original magma, they must have been very small.

Indirect evidence for the fluid character of the magma is the fact that there was a gravity separation of the crystals after intrusion. If the intruded material had been a "crystal mush" with very little liquid between the crystals, it is inconceivable that the crystals could move through this medium as they must have, under the influence of gravity, to form the remarkable layering parallel to the floors of the intrusions.

The temperature at the time of intrusion is assumed to have been around 1200° C. It is believed that this temperature was sufficient to render the magma fluid. Although the magma was perhaps peridotitic, it was by no means composed entirely of magnesium silicate. It contained the constituents of feldspar, augite, hornblende, and chromite, and an unknown quantity of volatile constituents, as well as those of olivine and bronzite. The estimate of 1200° C. is reached in the following manner: Diopsidic pyroxene occurs in contact-metamorphic rock at the contact. Its temperature of formation is above 700° C.[8] The temperature of the country rock is assumed to have been 200° C. at the time of intrusion. The temperature at an igneous contact is generally considered to be approximately the mean of the temperatures of the magma and the country rock. Therefore, the temperature of the magma can be estimated as follows:

$$\frac{t + 200^\circ}{2} = 700^\circ \text{ C.}$$

$$t + 200^\circ = 1400^\circ \text{ C.}$$

$$t = 1200^\circ \text{ C.}$$

The sequence of events is as follows:

(1) *Intrusion of an original homogeneous magma.* It is not possible to say just what the composition of the original magma that formed the Trout River laccoliths was, but it seems fairly evident from the general nature and distribution of the rocks that the original magma must have been peridotitic. This does not mean that it contained more than 75% of the constituents of olivine, but that the total content of ferromagnesian constituents was probably greater than 75%.

(2) *The formation of an ultrabasic border* probably took

---

[8] Ehrenberg: (2) found that diopside forms from a mixture of CaF_2 $CaCO_3$, MgO, and SiO_2 at 750° C. This is a single experimental observation and the temperature of formation may vary with concentrations and pressure. However, this figure is of the proper order of magnitude and can be used in an approximation of this kind.

place by rapid crystallization of olivine and bronzite, during which the crystals built upon one another and formed a solid layer. As crystallization became slower and took place away from the contacts, crystal settling could occur. Possibility of the formation of the border facies by chilling is eliminated because of (a) coarseness of crystallinity and (b) composition. As the magma gave rise to feldspar, augite, and hornblende by differentiation, it is obvious that the olivinic border facies does not represent a true chill zone.

(3) *Formation of the thick basal layers.* When the cooling effect of the roof and walls decreased and the crystals no longer formed rapidly into a continuous layer, but formed separately in the magma, each crystal sank as it reached a certain size and the crystals accumulated above the lower border facies. The thick basal zones may have formed entirely by crystal settling, or a part of the explanation may be that crystallization was facilitated near the bottom because of greater pressure, assuming that the temperature throughout the magma chamber was approximately uniform.

There may have been repeated injection of magma into the chamber during the formation of the basal layers, rather than a single huge injection. As long as olivine and bronzite were crystallizing, these successive pulsations would leave no record in the rocks.

The segregations of bronzite in the basal zone probably formed by a combination of crystal settling and growth of crystals along fractures in the intervening olivine layers. The thicker layers parallel to the floor must have formed by crystal settling. The cross-cutting vein-like bodies are thinner. They are definitely oriented over many square miles and appear to be related to a joint system in the intrusive body. In a few places some of the earlier bronzite segregations are acutely folded, probably by motion that took place after the formation of the segregations, but before the magma had completely solidified.

(4) *Formation of the first gabbro.* Eventually, after the separation of an immense amount of mafites, the residual magma became saturated with plagioclase molecules and bytownite began to crystallize. Pyroxene was still crystallizing, and thus was formed the gabbro above the pyroxenite. Finally the pyroxene almost ceased to crystallize and an anorthositic rock was formed. This does not mean that the magma had become anorthositic, but that it had become rela-

tively much richer in feldspar so that most of the crystals formed were of feldspar.

(5) *The critical zone.* The formation of the alternating layers of olivine-rich and feldspar-rich rocks of the critical zone offers a particularly difficult problem. The events thus far described may have taken place merely by crystallization and gravity separation. The lower layers are arranged in the order of the separation of their crystals and approximately according to specific gravity (of the unaltered rocks).

After a considerable thickness of anorthositic rock had been formed, one of the exterior factors mentioned above must have intervened. If the conduit had been kept open by pulsatory intrusion during the sequence of events thus far described, then it is quite possible that there was renewed injection of magma of the original composition at this time. The injection would raise the temperature of the restmagma and enrich it in the constituents of olivine. Further cooling would form an olivine-feldspar rock that might range from a feldspar-bearing dunite to a troctolite, depending upon the magnitude of the renewed injection as compared to the quantity of restmagma.

If the renewed injection did not saturate the restmagma with olivine at its elevated temperature, dissolving of olivine from the upper border facies might have completed the saturation.

Concomitant extrusion might possibly have been an accessory factor in this re-solution. However, the change in composition due to loss of volatiles from such a magma probably would not be great. Relief of pressure due to extrusion might aid somewhat, but all these things, if operative at all, were probably not major factors.

With further cooling the olivine would begin to crystallize first and an olivine-rich layer would be formed by crystal settling. Perhaps thin layers of dunite could form in this manner, but the majority of the layers should contain feldspar, or augite, or both, in addition to the olivine, because the magma would still be much richer in these constituents than was the original magma. Such is the case in the intrusive bodies of the Trout River area.

Continued crystallization would produce more gabbro, and eventually anorthosite, until another injection of the original magma took place. These leucocratic layers should contain olivine near their bases and be free from olivine in their upper parts. Such is the case.

If this hypothesis of origin is correct, then chromite should be formed with the olivine and should be confined to the olivine-rich layers, because it formed as an early mineral from the original magma. Furthermore, the chromite would be likely to take up some of the magnetite of the restmagma. This is logical in view of the fact that primary magnetite occurs in the gabbros, indicating that the magma was at times saturated with it. Chromite in the critical zone is confined to the olivine-rich layers, and it does contain much more iron than does the chromite of the border facies.

This process could be repeated any number of times until the entire mass had crystallized. The final fraction to solidify may have been either olivine-rich or feldspar-rich, depending on whether final solidification took place soon after an injection and on how much magma was injected in relation to the quantity of restmagma left at that time.

Unless there was extrusion of an equivalent amount of magma at the time of each renewed injection, the laccoliths must have grown in size after the formation of the border facies. This growth may have produced some of the jointing and faulting of the border facies, but it was not possible in the time available to study the jointing and faulting in great enough detail to determine what forces may have produced them.

Contact phenomena: *Roofs and sides.* The ultrabasic intrusives of the Trout River area have not brought about extensive changes in the sedimentary rocks into which they have been intruded. The effects produced above and on the sides of the intrusions are quite different from those produced in the floors. The shales and sandstones in contact with the upper parts of the intrusives have been baked and partly recrystallized, but have not been rendered schistose. There is very little evidence of pyrometasomatism. In the roof of the Table Mountain laccolith there is a 6-foot bed of sandstone that is separated from the intrusive rock by a layer of shale of about the same thickness. The shale has been hardened, partly recrystallized, and changed to green from the normal red color it shows farther away from the contact. The only observable effect of the intrusion on the sandstone is the formation of small amounts of chlorite and carbonate.

Floors. At the bases of the laccoliths the zone of metamorphism is much thicker than it is on the sides and tops. The floor of the North Arm Mountain body is exposed through considerable thicknesses in several cross-cutting canyons. Immediately below the contact the Humber Arm series has been changed to a rock composed mostly of diopsidic pyroxene, very slightly pleochroic amphibole, and plagioclase. The pyrobole (pyroxene and amphibole) crystals are oriented so that the rock immediately adjacent to the contact is almost schistose. The foliation planes are parallel to the contact.

The pyroxene disappears a few yards from the contact and the metamorphosed floor rock is composed of amphibole, plagioclase, zoisite, sericite, and carbonate. The amphibole is much more strongly pleochroic than is that nearer the contact. This facies of the rock is much finer grained than the pyroxene-bearing part and its schist-like structure is not nearly so well marked. It has, however, a definite cleavage parallel to the contact. Zoisite increases in amount away from the contact until it is more abundant than the amphibole. The floor becomes phyllitic still farther away from the contact and grades down into the slaty shale that outcrops along the shore near the head of the North Arm of the Bay of Islands.

The difference between the effects produced in the floors and those brought about in the roofs may have been due to (1) recrystallization and reaction caused by the high temperature and pressure under the laccoliths, with the orientation of the minerals controlled by pressure and the stratification of the sedimentary rocks, or (2) motion of the contact zones parallel to the floors after intrusion was complete. Absence of field evidence of such motion and the fact that higher temperature minerals occur nearer the contact favor the first possibility. Greater stress or movement near the contact would not explain the observed relations, because amphibole is more likely to form under stress than is pyroxene.

Dikes and sills are not numerous near the laccoliths. The contacts with the country rock, where they are visible, are practically all clear and sharp. There are a few thin sills in the floor of the North Arm Mountain laccolith. There are several sills and dikes in the roof (?) of the Table Mountain laccolith. These outcrop with the Humber Arm series on the east side of Trout River Harbor. No attempt was made to decipher a complete section across from the coast to Table Mountain, but samples of the sills and dikes were collected for study. The dikes are commonly less than 20 feet thick and are of basaltic composition. The sills range from 40 to 100 feet thick. They are diabasic in composition, for the most part, but at least one of them is peridotitic.

ACKNOWLEDGMENTS.

This study was the basis of a dissertation presented to the Faculty of the Graduate School of Yale University in candidacy for the degree of Doctor of Philosophy. The writer is greatly indebted to Professor C. O. Dunbar, not only for the opportunity of undertaking the study, but also for much aid in the field work and for many helpful discussions during the preparation of the dissertation. To Professor A. Knopf thanks are due for supervision of the laboratory work and for critical reading of the manuscripts of both the dissertation and the present paper.

BIBLIOGRAPHY

1. Daly, R. A.: Igneous rocks and the depths of the earth: New York, McGraw Hill, pp. 106-107, 1933.
2. Ehrenberg, H.: Über die Synthese von Diopsid und Forsterit . . . : Centralblatt für Mineralogie, Geologie, und Paläontologie, A, pp. 129-139, 1932.
3. Hall, A. L.: The Bushveld Igneous Complex: Jour. Chem. Met. Min. Soc. South Africa, Johannesburg, vol. 26, 160-174, 1926.
4. Niggli, P.: Die quantitative Klassification der Eruptivgesteine: Schweiz. Min. Petrog. Mitt., vol. 11, pp. 296-364, 1931.
5. Schuchert, C., and Dunbar, C. O.: The stratigraphy of western Newfoundland: Geol. Soc. America, Memoir I, 123 pp., 1934.

Yale University,
New Haven, Conn.

THE RADIUM CONTENT OF LAVAS FROM LASSEN VOLCANIC NATIONAL PARK, CALIFORNIA.

ROBLEY D. EVANS* AND HOWEL WILLIAMS.

OBJECTS AND METHOD OF STUDY.

The variation in the radium content of the dominant igneous rock types is fairly well-known. Comparatively little work has been done, however, to determine the variation within definite igneous provinces and to locate the distribution of the radium in the several rocks. It may be anticipated that when more studies of this type have been completed, especially if supplemented by petrographic descriptions and chemical analyses, much will be learned concerning the rôle of radium in igneous differentiation.

Studies of radioactivity have already been made on lavas from two regions of recent and present-day volcanism. Joly[1] has analysed many of the post-1631 products of Vesuvius, and Piggot[2] has examined many of the Hawaiian lavas. But the range of rock types in these fields is relatively small, and few other than basaltic flows are available. All the more desirable did it seem to us to determine the radium content of the lavas of the Lassen region. Here there is a wider variety of Tertiary and recent lavas than that of any other volcanic cone in the Cascade chain. Although andesites and dacites predominate, the flows range in composition from basaltic to rhyolitic. Moreover, abundant chemical analyses have already been made, the age-relations of the flows are well-known, and the principal types have been described and figured.[3] Accordingly, specimens were selected ranging in age from the oldest (upper Pliocene or lower Pleistocene) to the youngest (1915

---

* National Research Fellow.

[1] Joly, J.: On the Radioactivity of certain lavas. Phil. Mag., 18, 577-586, 1909.

[2] Piggot, C. S.: Radium in Rocks, III. The Radium content of Hawaiian Lavas, this Journal, 22, 1-8, 1931.

[3] Williams, Howel: The Volcanic Domes of Lassen Peak and Vicinity, California, this Journal, 18, 313-330, 1929. 3a. The Dacites of Lassen Peak and Vicinity, California, and their basic Inclusions, *idem*, 22, 385-403, 1931. 3b. Geology of the Lassen Volcanic National Park, Univ. Calif. Publ. Bull. Dept. Geol. Sci., 21, 195-385, 1932.

AM. JOUR. SC.—FIFTH SERIES, VOL. XXIX, NO. 173, MAY, 1935.
29

lava of Lassen Peak), and in composition from the most basic basalt to the most acid dacite.

The direct-fusion furnace technique was employed for removing the radon, which was then measured in a double ionization chamber apparatus,[4] all ionization currents being photographically recorded.[5] The apparatus was calibrated with a standard radium solution supplied by Professor S. C. Lind, which had been prepared from pure $RaCl_2$ previously compared with the International Radium Standard by the U. S. Bureau of Standards.[6]

We are greatly indebted to Professor C. A. Anderson for supplying specimens, descriptions, and analyses of the dacites of Bumpass Hell, and to Mr. Arthur Kip for assistance in carrying out the radium determinations.

PETROGRAPHIC NOTES.

The following brief descriptions are inserted for convenience of reference; fuller accounts may be found in two earlier papers. To correspond with the arrangement of the analyses in Table 1, the rocks are described in an order of increasing acidity.

1. *Basalt, Mount Harkness.* This dense dark gray basalt is the most basic lava flow yet analysed from the Lassen region, and is the poorest in radium. Pale green augite granules make up 35 per cent of the bulk; titanomagnetite 15; and about half the rock consists of microlithic labradorite. Interstitial glass is almost wholly lacking. Chemically, the flow is notable for its extremely high content of titania. Of all the Lassen lavas this resembles most closely the Oregonian plateau basalts. For a fuller description of the Harkness basalt see U. C. Bull.,[7] pp. 277-278; fig. 27B is of a similar lava.
2. *Basalt, northeast of Butte Lake.* A recent flow of blue black basalt composed of labradorite and augite, chiefly as microliths but occasionally as small phenocrysts, in a matrix of magnetite-charged glass. Feldspar comprises about 60 and augite about 20 per cent; olivine is a rare accessory. (U. C. Bull., p. 367; resembles fig. 60B.)

---

[4] Evans, R. D.: Rev. Sci. Inst., **4**, 223-230, 1933.

[5] Evans, R. D.: *idem*, **6**, 1935 (in press).

[6] Lind, S. C., and Roberts, L. D.: Jour. Amer. Chem. Soc., **42**, 1170-1177, 1920.

[7] Abbreviation for reference 3b.

3. *Basic inclusion, in old dacite of Lassen Peak.* From 40 to 50 per cent of a typical inclusion consists of labradorite laths; 40 per cent of basaltic hornblende, partly or wholly replaced by magnetite and, rarely, augite. A little biotite is present in most specimens. The residue is a clear, pale brown glass and, occasionally, a little interstitial quartz. The analysis quoted is of an inclusion similar to that tested for radium. (U. C. Bull. p. 331; also this Journal, 22, 398-399, fig. 6a, 1931.)

   A basic inclusion from the dacite of Raker Peak (not included in Table 1), is almost identical with the above. It carries 0.30 x 10^{-12} gram Ra per gram rock. Unfortunately no chemical analysis is available.
4. *Basic inclusion from dacite flow of 1915, Lassen Peak.* Contrasted with the hornblende-rich inclusions in the older dacites of the peak, the basic inclusions in the 1915 lava are devoid of that mineral. Hypersthene, green augite and relic grains of olivine are the ferromagnesian constituents; these with magnetite and andesine lie in a matrix of pale brown glass. (U. C. Bull., p. 333 and fig. 48; this Journal, 22, 400, fig. 7a, 1931.)
5. *Andesite, Raker Peak, roadside quarry on Hat Creek.* Pale gray lava consisting essentially of minute laths of andesine-labradorite (51 per cent), granules of augite (18), orthopyroxene (5), and a sprinkling of magnetite (2) in a glassy matrix (24 per cent). (U. C. Bull., p. 288; fig. 31B.)
6. *Andesite, near Supan's Springs, Brokeoff Volcano.* Half the rock consists of porphyritic acid labradorite; about a quarter of hypersthene with subordinate augite and the remainder of pale gray glass stippled with granular magnetite and microlithic labradorite. The analysis quoted is an average of four probably similar andesites of the Brokeoff Volcano. (Almost identical with lava illustrated in U. C. Bull., fig. 19A.)
7. *Andesite, Badger Mountain.* Brown glass ($n = 1.502 \pm .002$) makes up about half the volume; zoned phenocrysts of labradorite are plentiful; hypersthene exceeds augite in amount; granular magnetite is dispersed throughout. (U. C. Bull., pp. 238-240; differs from fig. 10B in paler color of glass, occurrence of magnetite in discrete grains, and in greater amount of hypersthene.)
8. *Dacite pumice, 1915 eruption of Lassen Peak.* Pale gray glass froth. Except that glass constitutes about 80 per cent of the volume and crystals only 20 per cent, the rock resembles the 1915 dacite described below. (U. C. Bull., p. 333.)

9. *Andesite, Crystal Lake.* The pale gray platy lava forming the cliffs overlooking Crystal Lake has this percentage composition: plagioclase (andesine and acid labradorite), 75; augite, 14; hypersthene, 5; magnetite, 4, and interstitial glass, 2. (U. C. Bull., pp. 221-222, fig. 5.)
10. *Dacite, Bumpass Hell.* Andesine is the chief phenocryst; with it are crystals of augite, hypersthene and quartz, a few badly altered flakes of biotite in a pilotaxitic base with a little interstitial glass.
11. *Dacite, 1915 eruption of Lassen Peak.* 60 per cent is a gray glass ($n = 1.485 - 1.500$) speckled with magnetite dust, granules of pyroxene and microlithic plagioclase; 30 per cent is made up of zoned phenocrysts ranging from oligoclase to acid labradorite; 5 per cent of porphyritic hypersthene and diopsidic augite, and the remainder of biotite, accessory basaltic hornblende, olivine, and quartz. (U. C. Bull., p. 332; this Journal, 22, 394-395, 1931.) Analysis quoted is not of identical specimen tested for Ra but an average of two similar rocks.
12. *Dacite, old lava forming bulk of Lassen Peak.* About a third of the rock is a pale glass, cloudy with magnetite dust and stippled with microliths of plagioclase; about half is formed of porphyritic andesine; the remainder consists largely of basaltic hornblende, fewer crystals of brown biotite, green augite, hypersthene, and quartz, attended by the usual magnetite and apatite. (U. C. Bull., pp. 330-331; this Journal, **22**, pp. 393-394, and fig. 4a, 1931.) Analysis quoted is an average of four similar dacites from Lassen Peak.
13. *Dacite, north dome of Chaos Crags.* A hornblende-mica hyalodacite with this percentage content: 40, colorless, pumiceous glass rich in potash ($n = 1.51$; U. C. Bull.) (Analysis 17, Table 1); 40, phenocrysts of oligoclase-andesine (anal. 16 of Table 1); 20, biotite, hornblende, hypersthene, augite, and accessory magnetite, apatite and quartz. (U. C. Bull., pp. 361-362; this Journal, **22**, p. 393 and fig. 5, 1931.) Analysis quoted is an average of two similar dacites from the same locality.
14. *Dacite, Raker Peak.* The most acid dacite and most radioactive of the Lassen lavas yet examined, consists of the following: colorless glass ($n = 1.499 \pm .002$; 45-60 per cent); phenocrysts of oligoclase-andesine (30 per cent); quartz (2 per cent), green hornblende, biotite and accessory magnetite and apatite. (U. C. Bull., p. 294.)

15. *Altered dacite, Bumpass Hell.* White, powdery exterior of an altered dacite block from a hot spring. Opal is by far the principal constituent; associated with it are kaolin, alunite and tridymite, the last-named partly residual but chiefly secondary.
16. *Porphyritic plagioclase from dacite of Chaos Crags.* Most of the feldspar phenocrysts in this lava are strongly zoned and reveal a range in composition between medium andesine and basic oligoclase.
17. *Glassy groundmass of dacite, Chaos Crags.* This acid, potash-rich glass ($n = 1.510$) is crowded with gas bubbles and lightly sprinkled with microlithic plagioclase and dusty iron ore.

DISCUSSION OF RESULTS.

As long ago as 1905, Lord Rayleigh[8] pointed out that there is in general a concentration of radioactive constituents in the acid rocks. The results of the present investigation add to the long list that verifies this generality. However, it will be seen from figure 1 that the content of radium in the Lassen lavas is far from being directly proportional to that of silica; the scattering of points on either side of the radium curve is wide. In this connection, it is of interest to note that Piggot[9] found the most radioactive of the Hawaiian lavas to be that poorest in silica, a nepheline-melilite basalt from Oahu, whereas the most siliceous and alkaline lava examined, a trachyte from near Hualalai, carries no more radium than the basalts of Kilauea.

The following table presents the average radium content of the main petrographic types in the Lassen region.

	Ra x 10^{-12} g./g.	Range	Average SiO_2%
Average of 2 basalts	0.33	0.30-0.35	51.13
Average of 3 basic inclusions ..	0.34	0.16-0.55	? 55.14
Average of 4 andesites	0.48	0.28-0.70	60.72
Average of 7 dacites	0.80	0.58-1.14	66.65

Figure 1 also shows that radium increases with the alkalies, especially with potash. A similar relation has recently been observed by Rössner[10] in the granite-diorite complex of the Gleinalmgebiet. Nor may it be fortuitous that the most

---

[8] Strutt, R. J.: (Lord Rayleigh), Proc. Roy. Soc., 77A, pp. 472-485, 1905.

[9] *Op. cit.*, 1931.

[10] Rössner, Hilde: Ueber den Radiumgehalt der Gesteine des Gleinalpenkerns, Min. u. pet. Mitt. 44, pp. 494-504, 1933.

TABLE I.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
SiO_2	47.43	54.83	55.14	57.16	57.85	59.62	61.93	62.62	63.50	63.80	63.86	67.24	69.04	70.93	92.20	65.77	76.75
Al_2O_3	13.19	17.05	19.10		16.71	17.43	16.37		16.76	17.55	16.96	16.53	15.69	14.31	1.02	21.51	12.32
Fe_2O_3	5.63	1.47	6.16		.88	2.62	1.15		1.49	1.28	1.24	3.60	1.02	1.30	nil		1.36
FeO	7.04	5.79	.54		4.93	3.12	3.90		2.80	2.44	2.91		1.64	1.26	.40	tr	
MgO	5.20	5.47	4.23		6.07	3.41	3.26		2.90	2.02	2.78	2.13	1.31	.94	nil		nil
CaO	9.39	7.72	8.36		8.30	6.57	6.24		5.80	2.60	5.16	3.89	3.23	3.24	.35	5.72	1.18
Na_2O	2.58	3.60	3.71		3.04	3.76	3.37		3.59	2.70	3.95	3.74	4.16	4.30	tr	5.92	3.55
K_2O	1.79	1.77	1.04		1.18	1.73	2.00		2.22	1.82	2.09	2.22	2.90	2.76	tr	.83	3.98
H_2O+	1.38	.73	.91		.32	.91	.74		.35	2.80	.41	.74	.59	.65	1.65	.34	.54
H_2O-	2.02	.27			.16		.18		.21	1.85	.08			.16	2.80		
TiO_2	4.00	1.25	.52		.60	.58	.60		.65	.55	.53	.36	.31	.26	1.25		
P_2O_5	.55	.42	.18		.13	.18	.16		.18	tr	.14	.07	.09	.12	tr		
MnO	.12	.11	.11		.09	.17	.08		.07	tr	.06	.04	.11	.06	nil		
BaO	.04	.03	tr		.02	.04	.04		.03		.05	.07	.07	.05	n.d.		
SrO	n.d.	n.d.	.07		n.d.	.02	n.d.		n.d.		.02	tr	.03	n.d.			
Total	100.36	100.51	100.07	57.16	100.28	100.16	100.02	62.62	100.55	99.89	100.30	100.63	100.19	100.34	100.05	100.09	99.68
Ra x 10^{-12}	0.30	0.35	0.16	0.55	0.36	0.28	0.60	0.80	0.70	0.58	0.70	0.81	0.67 0.93	1.14	0.35	0.05	?1.1

1. Basalt, Mount Harkness.*
2. Basalt, northeast of Butte Lake.*
3. Inclusion in old dacite, Lassen Peak.
4. Inclusion in 1915 dacite, Lassen Peak.*
5. Andesite, Raker Peak.*
6. Andesite, near Supan's Springs, Brokeoff volcano.
7. Andesite, Badger Mountain.*
8. Dacite pumice, 1915 eruption, Lassen Peak.*
9. Andesite, Crystal Lake.*
10. Dacite, Bumpass Hell.* Includes 0.48 SO_3.
11. Dacite, 1915 eruption, Lassen Peak. Includes 0.02 ZrO_2; 0.02 S; 0.02 F.
12. Dacite, old lava of Lassen Peak.
13. Dacite, north dome of Chaos Crags.
14. Dacite, Raker Peak.*
15. Altered dacite, Bumpass Hell.* Includes 0.03 S; 0.35 SO_3.
16. Plagioclase, from dacite of Chaos Crags.
17. Residual glass from same.

* Identical specimens analysed for radium and main oxides.

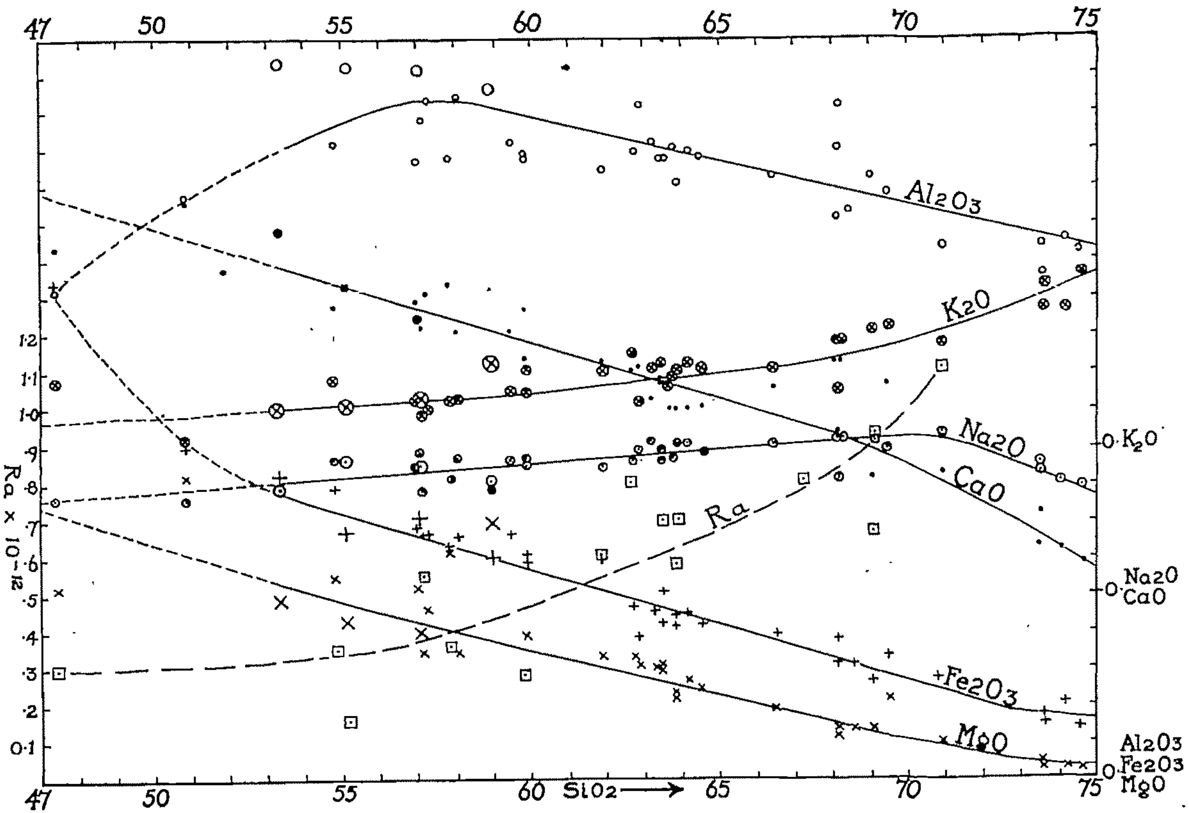

47
50
55
60
65
70
75
Al2O3
K2O
Na2O
CaO
Ra
Fe2O3
MgO
1·2
1·1
1·0
·9
·8
·7
·6
·5
·4
·3
·2
0·1
Ra × 10⁻¹²
0·K2O
0 Na2O CaO
0 Al2O3 Fe2O3 MgO
SiO2 →

Fig. 1.

radioactive lavas yet examined, those of Vesuvius, are, despite their basicity, unusually rich in potash (averaging more than 7 per cent K_2O).

As a whole the lavas of the Lassen region are relatively poor in radium. It is true that Urry[11] gives the mean value of 56 basalts as 0.28 x 10^{-12} gram Ra per gram of rock, but the only basalts poorer in radium than those of Lassen are the Keweenawan flows and certain basic lavas from the Gwalior Series in India. The Tertiary plateau basalts and those of Hawaii and Vesuvius, for example, are much more radioactive. Indeed in Poole and Joly's list[12] of the general means of radium contents of basalts, all contain more than twice the content of the Lassen basalts, and those of the Western United States contain 1.69 x 10^{-12} gram Ra per gram of lava. There is much less radium in the Lassen andesites than in those of Hungary[13] (1.64-2.38 x 10^{-12} Ra g./g.) and in that from Maui[14] (0.90 x 10^{-12}). Similarly, most of the acid lavas examined from other parts of the world are decidedly more radio-active than those of the Lassen region.

CONCENTRATION OF RADIUM IN THE LASSEN LAVAS.

The data concerning the location of radium in igneous rocks are meager. It may be of value to summarize them here. Waters[15] found that the light fraction and the magnetite of a rotted Cornish granite were non-radioactive. The residue was mainly tourmaline, but the radium was largely concentrated in anatase or rutile. In the Dalbeattie granite[16] he found it chiefly in allanite, with less in magnetite, titanite, and apatite; in the Mourne granite chiefly in zircon and some titaniferous mineral; and in a gneiss from the Inner Hebrides the radium was again concentrated in zircon. Fletcher,[17] examining the Leinster granite, discovered most of the radium in the zircon-bearing micas. In one specimen, the quartz contained no

[11] Urry, W. D.: The Occurrence of Radium, Uranium and Potassium in the Earth, Proc. Amer. Acad. Arts and Sci., **68**, pp. 137-144, 1933.

[12] Poole, J. H. J., and Joly, J.: The Radioactivity of Basalts and other Rocks, Phil. Mag., **48**, pp. 819-832, 1924.

[13] deFinály, S. S.: The Radium content of some Hungarian Rocks, this Journal, **24**, pp. 306-310, 1932.

[14] Piggot, C. S.: *op. cit.*, 1931.

[15] Waters, J. W.: Radioactive Minerals in common Rocks, Phil. Mag., **18**, pp. 677-679, 1909.

[16] *Idem*, 19, pp. 903-904, 1910.

[17] Fletcher, A. L.: The Radioactivity of the Leinster Granite, Phil. Mag., **21**, pp. 102-111, 1911.

radium, the feldspar 0.52 x 10^{-12} Ra g./g., and the muscovite 0.72 x 10^{-12} Ra g./g. One halo-bearing biotite carried as much as 11.87 x 10^{-12} Ra g./g.; Urry[18] observed that the bases of certain Keweenawan basalt flows were less radioactive than their upper parts, supposedly because they were less feldspathic. Holmes[19] states that the radioactive constituents in a pegmatite from Blueberry Mountain, near Boston, Massachusetts, are orangite-thorite, zircon, titanite, and allanite. In the Stone Mountain granite of Georgia, Piggot[20] found the muscovite to carry 27.5 x 10^{-12} Ra g./g., biotite 11.3 x 10^{-12}, but quartz and feldspar only 1.65 x 10^{-12} Ra g./g. The corresponding values in the North Jay granite of Maine were 20.7, 20.7 and 1.6 x 10^{-12} Ra g./g. Among the plutonic rocks of the Gleinalmgebeit, Rössner[21] found the most radioactive to be those rich in alkali feldspar and tourmaline; and Piggot states that uranophane is always found near relatively large accumulations of tourmaline in the Stone Mountain granite. Curiously enough, Piggot[22] determined the potash feldspars of the Stone Mountain granite to be less radioactive than the plagioclase. Hirschi,[23] in his studies of the intrusive rocks of the Aar massif, found that high potash values were associated with high content of radioactive elements of the uranium-thorium series, independently of the content of silica.

With rare exceptions, the lavas of the Lassen region do not lend themselves to a clean separation of their constituent minerals. All but a few are of such fine grain or of such a texture that isolation of the crystals is not practicable. Bromoform separations were made of the light and heavy constituents in the dacites of Lassen Peak and the north dome of the Chaos Crags. The heavy fraction of the latter dacite was then divided into weakly and strongly magnetic parts. Finally, by the use of a needle, porphyritic feldspars were extracted from untreated samples of the Chaos Crags dacite. The following results were obtained.

---

[18] Urry, W. D.: The Radium content of the Keweenawan Basalts and some accessory minerals, Proc. Amer. Acad. Arts and Sci., **68**, pp. 125-136, 1933.

[19] Holmes, Arthur.: Physics of the Earth, **IV**, Age of the Earth, Bull. 80, Nat. Research Council, pp. 342-343, 1931.

[20] Piggot, C. S. and Merwin, H. E.: Location and Association of Radium in Igneous Rocks, this Journal, **23**, pp. 49-56, 1932.

[21] Rössner, Hilde: *op. cit.*

[22] Piggot, C. S.: Radium in Rocks I, this Journal, **17**, pp. 15-34, 1929.

[23] Hirschi, H.: Radioaktivität der Intrusivgesteine des Aarmassivs. Schweiz. min. u. pet. Mitt., **7**, pp. 98-114, 1927.

Chaos Crags Dacite.

	$g \times 10^{-12}$ Ra per gram	% in rock	Proportional Ra value in 1 gram of rock	
Plagioclase phenocrysts	0.047	c.40	0.019	Dacite as a whole: 0.67×10^{-12} g./g.
Strongly magnetic heavies......	0.85	5.45	0.046	
Weakly magnetic heavies......	0.83	4.30	0.036	
		Total	0.101	

The strongly magnetic fraction is composed chiefly of magnetite and hornblende with a little glass adhering; the weakly magnetic fraction is almost entirely biotite with a slight admixture of hornblende. The remaining half of the rock is an acid, potash-rich glass (anal. 17, Table 1) with sporadic microliths of plagioclase and a little dusty magnetite. Assuming that no radium was lost during the bromoform separation—which seems to us a reasonable assumption—this residual glass must be the most radioactive part of the dacite and carries about 1.1×10^{-12} gram Ra per gram. Contrary to the experience of most workers, we find no marked concentration of radium in the mica. Neither did Joly in his studies of the Vesuvian ejecta. The lowest radium value which he obtained from any of the post-1631 lavas of Vesuvius was 7.8×10^{-12} gram Ra per gram, and yet a biotite from one of the lavas carried only 2.6×10^{-12} gram Ra per gram. The low radium value of the plagioclase in the Chaos Crags dacite should occasion no surprise.

Old Lassen Dacite.

	$g \times 10^{-12}$ Ra per gram	% in rock
Lava as a whole.............	0.81	
Light separates	0.81	95
Heavy separates	0.68	5

A clean mineralogical separation of the old dacite forming Lassen Peak was not possible. The light fraction consisted chiefly of plagioclase and pale glass, some of the glass containing dusty iron ores and rare crystals of biotite and hornblende. The heavy fraction was made up principally of iron ores, biotite, and hornblende. Again, contrary to the experience of most workers, we find no marked concentration of radium in the heavy minerals. Indeed, if the plagioclase of the Lassen dacite is as weakly radioactive as that of the Chaos Crags dacite, it seems probable that much of the radium is located in the residual glass or in its microlithic inclusions.

VARIATION OF RADIOACTIVITY WITH AGE.

In the basic, potash-rich lavas of Vesuvius, the content of radium is unusually high; moreover Joly found it to increase in general from the flows of 1631 to those of 1906. Similarly, Urry observed an increase of radioactivity from the oldest to the youngest of the Keweenawan basalts. On the other hand, Piggot's work on the lavas of Kilauea shows that a "very old lava" from the north edge of the crater, the 1870-1880 flow, 1894 and 1921 flows all carry 0.94 x 10^{-12} gram Ra per gram of rock. Likewise, Farr and Florance[24] could see no direct correlation between the age and radium content of certain igneous rocks from the sub-Antarctic islands of New Zealand.

Such data as we have from the Lassen lavas show no dependence of radium content on age. Indeed the oldest and youngest flows examined—namely those of Crystal Lake (Anal. 9, Table 1) and the 1915 dacite of Lassen Peak (Anal. 11)—resemble each other in their content of the principal oxides more closely than any of the other lavas of the region, and each carries 0.70 x 10^{-12} gram Ra per gram of rock. The old dacite of Lassen Peak is slightly more radioactive than the 1915 lava, but it is also more siliceous; a basic inclusion from the 1915 flow, though carrying only a little more silica, contains more than three times as much radium as an inclusion from the old lava forming the bulk of the peak. Of the two basalts tested, that from Mount Harkness is pre-glacial and the other is extremely recent, yet their radium contents are almost the same.

Finally, it should be remarked that of two samples of dacite from the north dome of the Chaos Crags, one contains 0.67 x 10^{-12} gram Ra per gram of rock and the other 0.93 x 10^{-12}. Yet in their content of the principal oxides the dacites of this protrusion vary little (U. C. Bull., p. 365), and under the microscope their mineralogical content appears to be quite uniform. The maximum observational uncertainty in the radium determinations is 0.02 x 10^{-12} gram Ra per gram of rock; the variation in the dacite is, therefore, a real one and implies a pronounced inhomogeneity of distribution within a single lava protrusion.

---

[24] Farr, C. C., and Florance, D. C. H.: Phil. Mag. 18, pp. 812-816, 1909.

INFLUENCE OF HOT SPRINGS.

Analyses 10 and 15, Table 1, are of fresh and altered dacites from Bumpass Hell. Although the ferromagnesian constituents, feldspars, and glass of the original dacite have entirely disappeared in the alteration, leaving a residue of almost pure opal, the radium content has only been reduced from 0.58 to 0.35×10^{-12} gram Ra per gram of rock. We are at a loss to account for the radium in the altered lava. Professor C. A. Anderson informs us that in certain mud pots in the Devil's Kitchen, there is a concentration of zircon, whether mechanically or by selective solution is uncertain, but he has detected none in the specimen from Bumpass Hell. Of the radioactivity of the Lassen hot springs nothing is known.

University of California,
Berkeley, California.

OESELASPIS, A NEW GENUS OF OSTRACODERM.

GEORGE M. ROBERTSON.

In 1931 Dr. Wm. Patten published a brief description of *Didymaspis pustulata* from the upper Silurian of the island of Oesel (1). Previous to that time this genus had been described very inadequately, practically nothing having been added in the few descriptions published since the original descriptions of Lankester (2, 3). In 1932, however, Dr. Stensiö (4) redescribed the material on which the genus is based, and his description indicates that *Didymaspis pustulata*, Patten, is not a member of the genus.

Didymaspis and Dr. Patten's species agree in the general form of the shield, including the slight emarginations which Stensiö interprets as representing the pectoral sinuses of Cephalaspids. The interzonal part of the shield is long in both, as in *Tremataspis*, and in fact none of the characters given in *Didymaspis* descriptions prior to that of Stensiö serve to distinguish the Patten species from that genus.

The most marked difference between the two types is that in *Didymaspis* the lateral sensory or electric fields are long and undivided, whereas in the Patten species the fields are divided and resemble those of *Tremataspis*. In *Didymaspis* the dorsal field extends just back to the apertures interpreted as endolymphatic, while in the Patten species these apertures lie posterior to the field, as in *Tremataspis*.

Since the genus name *Didymaspis* cannot apply to Dr. Patten's species, I propose for it *Oeselaspis pustulata*, n. gen. Whether the new genus belongs with the Tremataspidae or with the Cephalaspidae is uncertain. The presence of slight cornua would seem to place it in the Cephalaspidae. However, the divided lateral fields would make it exceptional in that family, whereas in this particular it would agree with the Tremataspidae. The rugose surface agrees with the Cephalaspidae rather than with the Tremataspidae. Further study may enable us to place it definitely in one family or the other, or may result in determining that this new genus represents a new family as well. It would appear as a further step from the Cephalaspidae via the *Didymaspis* type toward the Tremataspidae. Among the notes left by Dr. Patten was one page descriptive of this form on which he had suggested that

Didymaspis be raised to a new family on the basis of this material. Stensiö's study appears to establish *Didymaspis* among the Cephalaspidae, but I am inclined to Dr. Patten's suggestion regarding *Oeselaspis.*

Oeselaspis pusulata is a small form. Dr. Patten's type was described as having a shield about 19 mm. wide by 29 mm. long. With the larger number of specimens which have now been examined it appears that the average specimen is somewhat broader than this, ranging up to about 25 mm. The length is also somewhat variable.

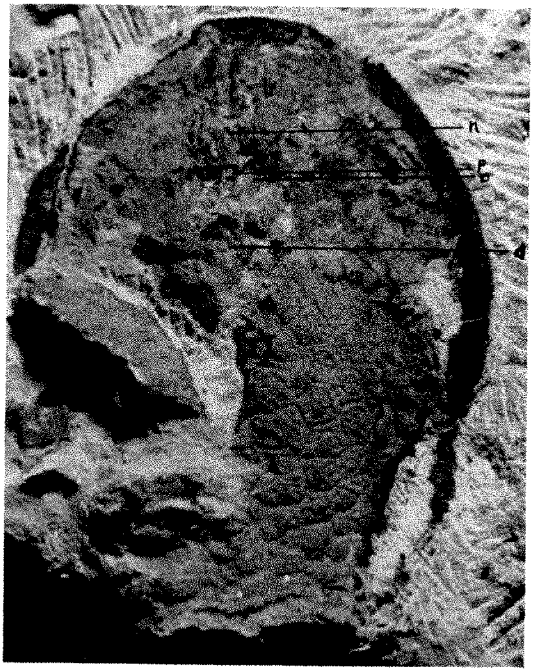


Fig. 1. Eroded dorsal shield of *Oeselaspis pustulata.*

The general form of the dorsal shield is similar to that of *Didymaspis grindrodi* (Figs. 1, 2). The anterior is bluntly rounded, with no indication of a rostral angle. The lateral margins about half way back are bluntly emarginated, forming shallow indentations which probably correspond to the pectoral sinuses in Cephalaspidae. No traces which can be identified as pectoral appendages lying in the region of these sinuses have been detected in the present material, nor has any account of their occurrence in *Didymaspis* been presented. The cornua, if such the antero-lateral region of the sinuses can be termed, also resemble those of *Didymaspis*. The margin of the shield anterior to the cornua is ornamented with fine, tooth-like tubercles. Posterior to the cornua this ornamentation is lacking. In one or two specimens a blunt dorsal median spine at the posterior end of the shield is indicated. The exo-skeleton of the posterior margin is somewhat thickened, as is best seen in ventral view of the dorsal shield (Fig. 2).

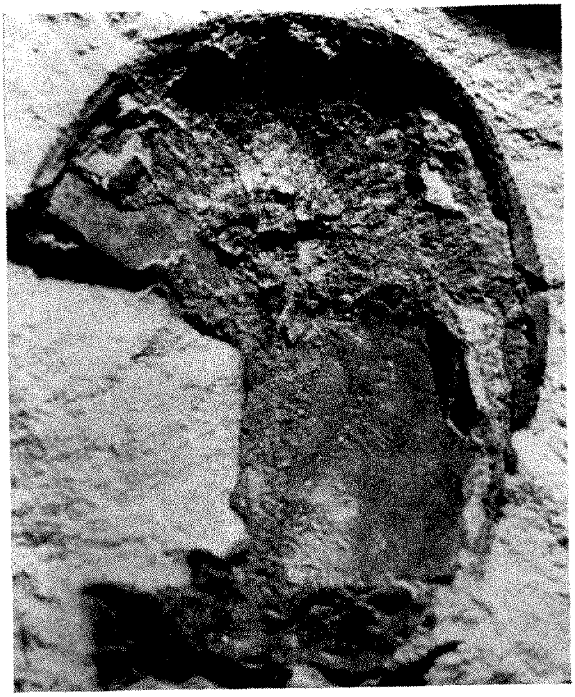


Fig. 2. Dorsal shield in ventral view.

No trace of the trunk and tail region posterior to the shield has been discovered. The form of the posterior portion of the shield indicates that it must have been roughly circular in section. The interzonal region of the ventral shield extends further back than does that of the dorsal shield. Comparison of the conformation of the posterior margin of *Oeselaspis* shields with the figures of *Didymaspis* given by Stensiö (4: P. 173; Pls. 54, 55), demonstrates another difference between the two forms. Whereas in *Didymaspis* both dorsal and ventral shields end in concavities, save for the slight protrusion of the dorsal spine, in *Oeselaspis* the median dorsal portion is convex (Fig. 2), and flanking it are concavities which are continuous with the concave lateral margins. The ventral margin is broadly convex (Fig. 4), except for the median portion, which has a slight concavity, flanked by small denticles.

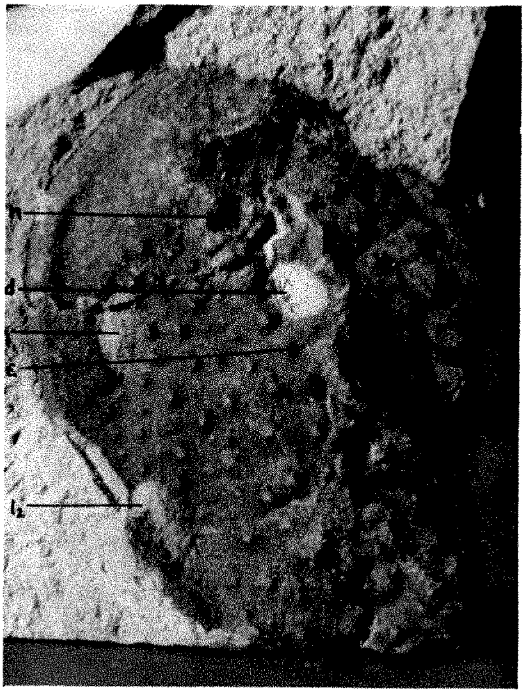


Fig. 3. Incomplete dorsal shield.

Both dorsal and ventral shields are convex both longitudinally and transversely, indicating a rather pot-bellied form (Fig. 4), broadest at the cornua, bluntly rounded anteriorly, narrowing considerably posteriorly. Transverse ridges occur near the posterior margins of both dorsal and ventral shields, on the inner aspect. The dorsal ridge has slight grooves anterior and posterior to it (Fig. 2). The ventral ridge is low and broad.

Dr. Patten interpreted the shield as being semi-membranous, flexible. The distortion without fracture, as well as the state of preservation, lends itself to this interpretation. The dorsal interzonal exo-skeleton is somewhat heavier than that of the anterior part (Fig. 2).

The outer surface is minutely spiculate. Larger pustular elevations also occur (Fig. 3), each in the center of what appear in deeper layers as polygonal areas. These occur on both dorsal and ventral surfaces in the interzonal region (Figs. 1, 4), and also on the dorsal surface in the cephalic region proper. There are indications that the pustular elevations were capped by glistening tubercles or nodules. In contrast to the condition in *Tremataspis* and in *Dartmuthia*, and

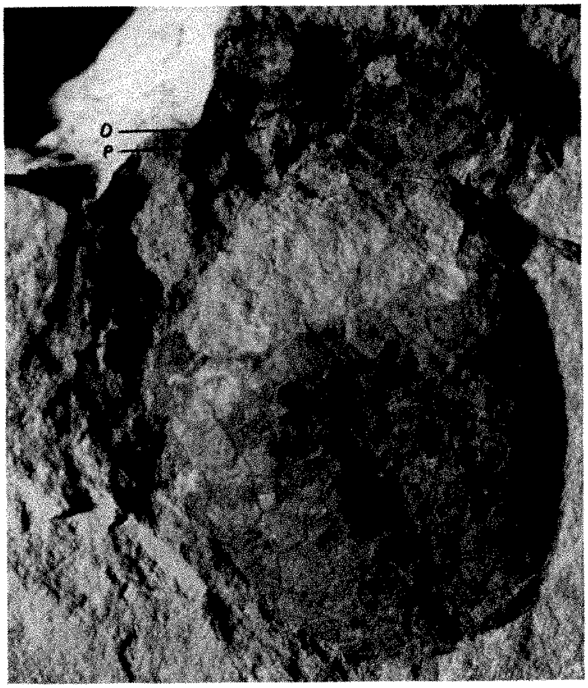


Fig. 4. Impression of inner surface of ventral shield, with inner surface of anterior portion of dorsal shield. d, dorsal field; e, endolymphatic aperture; l, lateral field; n, naso-hypophysial aperture; o, orbit; p. pineal. All figures x approximately 3.

more in conformity with that in Cephalaspidae, the cleavage usually carries away the actual spicules and nodules, so that these are only to be observed in specimens which have fractured vertically, on the exposed edge of the shield; or to be revealed by dissecting away the covering matrix with extreme care. Then they appear like tiny spicules of jet and somewhat larger nodules, similar to the smallest of those occurring on the surface of *Dartmuthia*. At the posterior margin of the ventral shield there occur some nodules, more or less tooth-like, and in the specimens in which they are available slightly curved downward. Whether this indicates that the caudal region was equipped with similar nodules cannot be determined, but in some other forms the posterior region of the shield to some extent anticipates the ornamentation of posterior segments. The polygonal areas are best seen in the interzonal region in the deeper layers of the exo-skeleton, where they appear with raised margins and depressed centers, the center of each showing a darker area corresponding to the pustular elevation on the outer surface.

The naso-hypophysial aperture is proportionately rather long, though less than in *Didymaspis*. As usual it lies in the center of a circum-nasal fossa. In some specimens a median constriction is observable. The orbits are small, oval, and close together. No sclerotic exo-skeleton like that in *Tremataspis* and in *Dartmuthia* has been observed thus far, although further dissection may disclose traces of one. The pineal aperture is relatively large. No indication of a pineal plate such as occurs in *Cephalaspis*, *Trematapsis*, and *Dartmuthia* has been found. Since preservation of this feature is always rare its absence does not indicate its non-occurrence. The orbital region is rather far back.

The post-orbital organ which Stensiö labels the dorsal electric field is separated from the pineal by about the same distance as separates the pineal from the nasal aperture. In one specimen there appears a definite elevation between the pineal and the dorsal field. This elevation takes the form of a rounded transverse ridge with two slight swellings toward its ends. The dorsal field itself is short and broad, somewhat variable in outline, but in general more or less spindle shaped, with the long axis in the longitudinal axis of the shield. In the form of this organ it thus shows another distinction from *Didymaspis*. The dorsal field does not extend back to the endolymphatic apertures, which lie in relation to it about as do those in *Trematapis* (Fig. 3). The paired apertures which Stensiö interprets as those of the canals of nerves to the dorsal field are situated as in *Didymaspis.*

The mid-dorsal ridge of the shield starts posterior to the dorsal field. It is not very pronounced. Near the posterior end there are three or four rounded elevations, more pronounced than the pustular ornamentation of the general dorsal surface.

The lateral fields resemble those of *Trematapis,* in that, instead of a single area on either side, extending most of the distance from a point lateral or antero-lateral to the nasal aperture back to or on to the cornua, there is a pair of short, more or less oval fields on either side, the anterior field being almost lateral to the nasal aperture, the posterior somewhat postero-lateral to the dorsal field (Fig. 3). In no specimen thus far uncovered is there any trace of plates covering the dorsal or lateral fields. It has not proved possible to trace the connections of the nerve canals to the lateral fields. From the traces of these canals which are preserved it appears that there were probably three such nerves to the anterior, and two or possibly three to the posterior field. Whereas in *Cephalaspids* generally and in *Dartmuthia* these nerves branched near the inner margin of the field, portions of the canals of the finer branches being preserved, in *Oeselaspis* they appear to enter the organ itself unbranched.

The exo-skeletal elements of the oralo-branchial region are seldom preserved in Osteostraci, such elements apparently having been embedded in membranous material which released them upon disintegration of the soft parts. Few of the specimens of *Oeselaspis* show any trace of this region of the ventrum. Of the form of the oralo-branchial chamber no single specimen gives a complete picture. However, by piecing together information derived from several specimens it becomes clear that this chamber had very nearly the form it shows in *Trematapis.* The posterior margin differs from that in *Trematapis* in showing a less pronounced median projection. The marginal processes which extend inward from the lateral margin, interpreted as inter-branchial ridges, are found in a number of specimens. The row of gill apertures extending diagonally inward from either side at the posterior end of the chamber resemble the same structures in *Trematapis* and *Dartmuthia,* although no specimen shows the rows in completeness. There appear to have been at least four, possibly five, such apertures on each side, which would indicate the total number on either side, including those opening on the lateral margins, as eight to ten.

In a number of specimens the dorsal surface has eroded or split off sufficiently deep in the anterior region to disclose the endo-skeleton of the gill-pouch region. Except in detailed features these structures were as in other members of the order. Whatever may have been the real nature of the structures represented in the fossils by this series of skeletal ridges and depressions, it is difficult to correlate them with any structure known in extant vertebrates except the gill pouches of Cyclostomes. The greater the number of specimens which pass through one's hands the more this impression gains.

In some of the Osteostraci specimens have been preserved with more or less of the exo-skeleton of the oralo-branchial chamber. From the small number which have been described it appears that two conditions were to be found. In the Cephalaspidae the region was apparently armored with a fairly large number of small plates. In the Tremataspidae the plates were fewer and larger. The reconstruction of the oral region of *Tremataspis schmidti* which Dr. Patten made as a result of examining a specimen in the museum at St. Petersburg, plus information gained by working over some other *Tremataspis* specimens in the same museum and in a small collection of his own (5), is so often reproduced as to be familiar. A second reconstruction of the same species, based on some of the very abundant material of that genus in his own collection, was published in his last paper (6). In addition to these published figures there are in the Patten collection at Dartmouth College a number of Tremataspids showing this region, some of them fairly complete. In *Dartmuthia* the condition resembled that in *Tremataspis* (7). The material of *Oeselaspis* offers no specimens with these plates preserved sufficiently to determine the structure, but one specimen shows an impression properly situated to have been that of an oral plate, one of the posterior group. This impression would indicate that at least the posterior plates were of fair size.

The superficial surface is very poorly preserved, and thus far it has not been possible to discover any trace of a sensory canal system such as is present in other Osteostraci.

The material in the Patten collection definitely assignable to the genus comprises 48 specimens, some of which are quite fragmentary. There are in addition other specimens which probably belong to *Oeselaspis* but have thus far proved impossible to identify definitely. The generic and specific characters which can be used as diagnostic thus far, that is the form and ornamentation of the shield and the character of the lateral electric fields, may be augmented on further study by characters identifiable in specimens showing none of the at present essential portions.

I wish to acknowledge my obligation to Mr. Henry Barrett, Dartmouth College Photographer, for the illustrations in this paper.

BIBLIOGRAPHY.

1. Patten, W.: New Ostracoderms from Oesel. Science, June 19, 1931, Vol. 73, No. 1903.
2. Lankester, E. R.: On Didymaspis, a new Genus of Cephalaspidian Fishes. Geol. Mag., Vol. 4, 1867.
3. Lankester, E. R.: A Monograph of the Fishes of the Old Red Sandstone of Britain. Part I. The Cephalaspidae. Paleontographical Society, London, 1870.
4. Stensiö, E. A.: Cephalaspids of Great Britain. London, 1932.
5. Patten, W.: On the Structure and Classification of the Tremataspidae. Mem. de l'Academie imp. des Sciences de St. Petersbourg. Ser. 8, Vol. 13, No. 5, 1903.
6. Patten, W.: Foundations of the Face. Scientific Monthly, Vol. 35, Dec., 1932.
7. Robertson, G. M.: The Ostracoderm genus Dartmuthia, Patten. This Journal, Vol. 29, No. 5, April, 1935.

Dartmouth College,
Hanover, New Hampshire.

DISCUSSION AND COMMUNICATIONS.

PALEOZOIC PLANKTON OF NORTH AMERICA.

A very suggestive and thought-stirring memoir is Ruedemann's "Paleozoic Plankton of North America" (Geol. Soc. America, Mem. 2, 1934), dealing with a difficult subject which he has long had under study. It has to do, as the title indicates, with the fossil representatives of floating or planktonic life found in the shallow-water deposits of epicontinental seas, and more particularly with the typical graptolite associations.

Part II of the memoir (pp. 67-97) is concerned with the rare fossil associates of the graptolites, of which 49 are described, divided among 12 classes of organisms; 22 new species and 3 new genera (2 cnidarians and 1 worm) are proposed. These form the essential basis of the author's conclusions.

Part I (pp. 7-67) is a searching analysis of the small faunas in the typical graptolite associations, distinguishing the various invertebrates that live on the bottom (benthos) from those that swim above it (nekton) and those that float in the surficial waters and thus exist independently of the bottom (plankton). An analysis of the faunas living at present in the littoral seaweeds and sargasso seas is followed by an account of the Paleozoic plankton in general, and finally the conditions of black-shale making are discussed, along with a survey of the black-shale faunas as recorded in the strata of North America. In this analysis of the faunas, the critical reader will find much detail to question, or will want more evidence before adopting the author's view. This attitude, however, is anticipated by the author, since so little is as yet established regarding the actual habitats of the Paleozoic plankton. This path-finding memoir is, in fact, presented with the hope that it will stimulate discussion and lead to further research.

The essential premises of the memoir are that the typical black-shale faunas of the Ordovician and Silurian were planktonic in habitat, that they were usually composed of small individuals of oceanic (sargasso-sea) origin, and that, by means of oceanic currents, this life has been floated into the geosynclines and interior seas of the continents, where it is preserved, in the main, in black, aluminous, exceedingly fine-grained shales. In presenting these conclusions as the correct interpretations deduced from the evidence presented, Ruedemann is satisfied that throughout Paleozoic time there was an abyssal Atlantic Ocean with a sargasso sea, situated between Europe and North America, and in dimensions much like the ocean of the present time. Accordingly, the graptolite faunas of the geosynclines are, to him, "the most damaging evidence to the drift theory yet brought forward." The present writer wishes he could concur in this belief, but, although he agrees that there was a large Paleozoic Atlantic Ocean (Poseidon), he cannot believe that the graptolite faunas in themselves prove the existence of an oceanic sargassum.

Graptolites are found in best preservation and in greatest variety and abundance in very fine-grained black shales. On the other hand, at various times and in many different places, they are preserved in other kinds of mudstones, and here they are associated with a greater variety of bottom life. Graptolites also occur in limestones, in an excellent state of preservation, and even in sandstones and dolomites. These varying occurrences indicate to the present writer that the graptolites were distributed by the marine currents throughout the epicontinental seas, and fell on all kinds of bottoms. In his opinion, their preserval depends less on the nature of the sediments than on the chemical and environmental conditions prevailing on the bottoms. The foul and exceedingly soft black sulphurous mud bottoms kill the organisms, embalm them, and preserve them as pseudomorphs, or take impressions of them such as are seldom if ever made on other kinds of sediments. Note that it is not only graptolites that are so preserved, but other invertebrates as well, most of which had chitinous or phosphatic tests (and some, no skeletons at all), as in the faunas of the Burgess and Utica shales, and those of Little Metis, Bundenbach, etc. The various organic types have fallen on all kinds of bottoms since the early Paleozoic, and yet their preservation is the exception and not the rule. Apparently the best conditions for preservation of the general external form of such organisms are present when they possess chitinous or phosphatic types of tests, and when these tests fall into sulphurous bottom muds. Elsewhere such life is largely destroyed by scavengers, dissolved away, or ground to pulp by the bottom waters. As is well known, the first requisite for the preservation of life as fossils is immediate burial, and no deposits are quicker to engulf the falling organisms than the soft black oozes with their high water content.

The free-floating graptolites are most common in the deposits of geosynclines and their embayments, but this is mainly because in these sequences black shales are more general in occurrence and far thicker, on account of the nearness of the lands furnishing the muds. Although graptolites are of very wide occurrence in the interior seas, they are of limited variety, as is shown in the Ordovician of the Cincinnati region, in the Maquoketa formation of Iowa and Illinois, and in the Silurian of western New York. These occurrences Ruedemann explains as due to "occasional and incomplete incursions, or overflows, from the geosynclines" (p. 9). They are not, however, cases of occasional or accidental dispersal, but are the records of stratal conditions which must have endured through tens of thousands of years. Furthermore, it seems to the writer that Ruedemann has not made enough allowance for the imperfection of the geologic record due to absence of fossilization.

We congratulate the author on showing us that plankton faunas have existed since at least earliest Ordovician time, but that these planktonic and epiplanktonic faunas originated in sargasso seas of the oceans is questionable, and the writer does not see that Ruedemann has proved or can prove his conclusions. It is not possible to do so, because of the nature of the evidence. The sargassum of the central Atlantic is a vast whirl whose planktonic life consists mainly of one genus of bottom-attached seaweed derived from the surrounding shallow tropical waters, and on and in these floating fronds lives the characteristic fauna. At death, this life rains into the abyssal depths, but as yet we do not know the nature of the deposits formed at such depths. On the other hand, an Atlantic realm (Poseidon) was probably present throughout Paleozoic time, and it may have had its sargassum, but that the pelagic faunas of the Paleozoic of North America and Europe originated in such whirls, the writer thinks cannot be demonstrated. In the main, he objects to the ideas that these pelagic faunas were of sargassal origin, and that they were distributed by the oceanic currents to the epicontinental seas. Why not the other way around? Why not say that these pelagic faunas originated in marginal or inland seas, and from them spread into the oceans and thus throughout the world? We need postulate no sargassum as the birthplace of all floating life; rather are such areas the asylums found by pelagic life. Furthermore, in the interior seas we know of no abyssal deposits, and such great depths are not necessary for the origin and evolution of pelagic life. As is well known, micropelagic life was primal in origin and it has long been universal in distribution.

We agree with Ruedemann that the typical graptolite shales were formed in the quiet marine waters of inland seas where no abyssal depths existed. They were made in current-less bottom waters, not only in the geosynclines, but in the epeiric seas as well, in shallow places behind headlands and spits, in small and large depressions of the sea bottoms, in connection with eddying waters, in cul-de-sac embayments, etc. In all such more or less currentless marine bottoms there is a decided tendency for the waters to lose their oxygen and to become foul, sulphurous, and destructive to life.

CHARLES SCHUCHERT.

SCIENTIFIC INTELLIGENCE.

CHEMISTRY AND PHYSICS.

Chemical Kinetics and Chain Reactions; by N. SEMENOFF, International Series of Monographs on Physics, Oxford at the Clarendon Press, 1935. Pp. xii, 480; 148 figs. Price $10.50.—This book gives a comprehensive and authoritative treatment of our present, somewhat limited, knowledge of a very important and, during the last few years, very intensely studied subject. This is shown particularly by the fact that the number of papers dealing with chain reactions that have appeared since 1930 is by this time well over 300. The book is well written with a physicist's point of view, stressing very strongly the purely theoretical aspect of the subject. Part I gives first a short historical introduction indicating the general foundations of the chain reaction theory. Then follows a treatment of the rather simple mathematical apparatus employed at the present time for the study of branching and non-branching chain reactions. Applying the ideas stated in Part I, Parts II-IV give an analysis of the existing experimental data for about fifty different reactions. The cases treated include 15 halogenation, 15 oxidation, 11 decomposition and 3 polymerization reactions. In the third group is included a number of explosion reactions like the explosion of nitroglycerin, trotyl, mercury fulminate and other compounds.

At the end of Part IV the author makes a summary of the general conclusions that he has drawn from his analysis of the experimental data. The author finds that "the overwhelming majority of chemical processes prove to be definite chain reactions." "The propagation of the reaction chains proceeds equally well in the gas and in the liquid phase as well as in solutions and sometimes in solid substances." "It appears that the kinetics of any chemical reaction is that of a chain mechanism and that the particular cases involving, for instance, reactions with very short chains or those elementary reactions requiring but little energy of activation, which can be interpreted without recourse to chains, are rare." Eight different criteria are given as tools for the testing of these statements and the author finds that to everyone of the reactions studied at least two of his criteria seem to apply.

The above may give an indication of the extreme importance the author attaches to the chain reaction theory in the field of chemical kinetics. His reaction analysis is, however, in several cases based on practically only qualitative experimental results, the interpretation of which is shown to be far from certain or even opposed by contradictory results. Although his general conclusions, therefore, still are open to reasonable doubt, his book has a very high value as the first comprehensive summary of our present knowledge of chain reactions and a thorough study of the book is highly recommended to all chemists interested in the field of chemical kinetics.

G. C. AKERLOF.

Soil Analysis: A Handbook of Physical and Chemical Methods; by C. Harold Wright. Pp. viii, 236; 6 figs. London, 1934 (Thomas Murby and Co., 12s., 6d.).—During recent years many new chemical and physical methods have been applied to soils research. Heretofore investigators have been obliged to glean these from numerous journal papers and bulletins. The author has brought together a valuable collection of the workable methods recently proposed, in addition to older technique which is still in common use.

The book is in three parts. Part I, *Physical Methods*, gives details relative to mechanical analysis, soil colloids, moisture and other physical constants. Hydrogen ion concentration methods are also included. Part II, *General Chemical Methods*, presents various methods for determination of the important chemical elements in the soil. Part III, *Special Chemical Methods*, includes determinations involved in studies of soil extracts, base exchange relationships and soil forming processes. An appendix includes common tables most frequently used by the soil analyst.

The selections are drawn from publications of reputable scientists, engaged in soils research throughout the world. The essential details of the methods are carefully presented, with numerous helpful comments by the author. This book provides an excellent working tool for those interested in soil science and related fields.

M. F. MORGAN.

GEOLOGY AND MINERALOGY.

Guide to the Geological Model of Ardnamurchan; by J. E. Richey. Memoirs of the Geological Survey, Scotland. Pp. vi, 49; 11 pls. Edinburgh, 1934 (Price 1s.).—This report, as its title indicates, is to serve as an explanation to the geological model constructed on the scale of 4 miles to inch, of the Ardnamurchan Peninsula, which is the westernmost part of the mainland of Scotland. The report is essentially a condensation of the notable memoir on the Geology of Ardnamurchan, by J. E. Richey and H. H. Thomas, which was published in 1930. Most of the illustrations are reproduced in the present report and show the three successive centers of intrusion, each surrounded by a remarkable assemblage of ring-dikes and cone-sheets. The colored geologic map of the original memoir is here reproduced in black and white. It represents not only one of the most extraordinary Tertiary igneous complexes in the world but is also a lasting monument to the skill and ingenuity of the geologists who deciphered its astounding complexity.

ADOLPH KNOPF.

Geography and Geology of the Region Including Cape Cod, the Elizabeth Islands, Nantucket, Marthas Vineyard, No Mans Land and *Block Island*; by J. B. Woodworth and Edward Wigglesworth. Pp. xvi, 322; 38 pls. Memoirs of the Museum of Comparative Zoology at Harvard College, Vol. 52, Cambridge, 1934 ($15.00).—No area of Pleistocene glacial features east of the classic Great Lakes region has deserved a thorough study with detailed publication of results, more than the Cape Cod district. Lying in the zone of the drift border, and underlain by weak coastal-plain strata, it must early have been expected to yield a better record of pre-Late-Glacial events than other parts of New England. The thorough and painstaking work of Woodworth and Wigglesworth has justified this expectation.

For the senior author the work is posthumous. Carried out mainly in 1914 and 1915, the field work was, however, begun by Woodworth before 1900, and is based in part on the excellent earlier studies made by Shaler. Necessarily the bulk of the discussion is directed to the Pleistocene, as the pre-Pleistocene coastal-plain features are exposed in only a few places. The authors give, however, as good a picture of the earlier history as the limited exposures of Cretaceous, Miocene, and Pliocene strata permit.

The Pleistocene record is held to be fourfold, involving the four glacial stages of the standard Mississippi Valley section. Whether this interpretation stands or is modified in the light of further study, the thorough and detailed character of this monograph will compel its acceptance as a standard reference and as a point of departure for future studies.

Few books can boast as rich and beautiful a format, with fine paper, wide margins, abundant heliotype reproductions of photographs, and adequate detailed areal maps, scale 1:62,500. R. F. F.

Molecule e Cristalli; by Enrico Fermi. Pp. 303. Bologna, 1934 (Nicola Zanichelli, Editore, 50 lire).—This is a mathematical study of the various problems connected with the theory of chemical molecules and the relationships that exist between them and the structure of crystals. The book is divided into three parts. Part I treats of molecules with the following division into chapters: 1, The chemical bond; 2, Spectra of bi-atomic molecules; 3, Thermal properties of bi-atomic molecules. 4, Poly-atomic molecules. Part II concerns crystals and has the following chapters: 1, Geometry of crystal lattices; 2, Physical properties of crystal lattices. Part III is entitled *Quantum statistics*. Its two subdivisions are: 1, Statistical equilibrium between quantum states; 2, The quantization of gases. W. E. F.

MISCELLANEOUS SCIENTIFIC INTELLIGENCE.

The Scientific Basis of Evolution; by THOMAS HUNT MORGAN. Pp. xiii, 306. New York, 1935 (W. W. Norton and Co., price $3.50).—The first edition of this book, published three years ago, made available to the general reader the substantial evidence which recent discoveries in genetics have to offer in support of the evolutionary theory.

The most recent studies of the cellular mechanism by means of which at least some of the changes of evolutionary significance occur have afforded startling confirmation of previous theoretical conceptions; the physiological properties of the genes, both in development and evolution, take on a new significance as a result of the newer evidence; the ever-debatable question as to the possibility of the inheritance of so-called acquired characteristics has been re-examined, and the influence of geographical isolation as a factor in evolution has been reconsidered. These topics are discussed in the final chapter of this new edition and must be taken into account by any one who wishes to keep in touch with the rapid progress which is now being made in this important branch of biology. W. R. C.

The Philosophy of a Biologist; by J. S. HALDANE. Pp. xii, 155. Oxford, 1935 (Clarendon Press, price $2.50).—The author, who is noted for his many fundamental contributions to physiology, has in his later years been forced to the opinion that science is only a partial representation of reality. His reasoned conclusions, based on his own experience in science, as to the relations between philosophy and physical science, biology, psychology and religion, deserve thoughtful consideration by every reader of this stimulating little book. W. R. C.

ANTONIO RODOLICO (1911-1932), *Ricerche di Biologia*; compiled by NICCOLO RODOLICO. Pp. xv, 153, with 10 pls. Firenze, 1934 (Felice le Monnier).—A reprint of five of the nine contributions which this brilliant young biologist published during his brief career. The most extensive and important of these deals with the sexual differentiation and the development of the germ cells of the eel—subjects that had puzzled biologists for more than a century. W. R. C.

The Science of Rubber; edited by R. F. DUNBROOK and V. N. MORRIS. Pp. xvi, 770; 213 figs. New York, 1934 (Reinhold Publishing Corporation, $15.00).—"The Science of Rubber" is a translation of "Handbuch der Kautschukwissenschaft," which is edited by K. Memmler in collaboration with a group of distinguished German scientists interested in rubber. It has been said that the theory of to-day is the practice of to-morrow, and this is sometimes true, but it is more likely that the practice of to-day is explained by the theory of to-morrow. Man finds by experiment,—by trial and error, if you will—how to make use of the materials which Mother Nature has given him, but industries become aged before the theoretical interpretations of their foundations are worked out. Rubber is one of those unique substances which for many years has defied most attempts to unravel its secrets: even to-day an adequate explanation of the chief process for making rubber useful, namely, vulcanization, is still lacking. The advance still goes on and the day seems now not far distant when this and many other of the "secrets" of rubber will be fully known and understood. Much of the excellent chemical and physical work on rubber is in scattered articles in different scientific and technological journals, and in special books. The book under review is the first attempt to gather together the best of this information in one volume. An idea of its scope and of the excellence of its treatment can be gathered from the following list of subjects and authors: Introduction, including History and Statistics of Crude Rubber, Botany, Cultivation, Collection and Preparation of Rubber, A. Zimmermann; Chemistry of Rubber, R. Pummerer and A. Koch; Vulcanization of Rubber, E. Kindscher; Analytical Testing Methods, E. Kindscher; Physics of Rubber, L. Hock; Physical Testing Methods, K. Memmler and A. Schob; Microscopy of Technical Vulcanizates, H. Pohle.

The translation was edited by R. F. Dunbrook and V. N. Morris, in collaboration with members of the research staff and laboratories of the Firestone Tire and Rubber Company. This Company deserves much credit for allowing able members of its research organization to produce a translation of so important and useful a scientific treatise as this.

The translators have kept to the general arrangement of the original but have corrected certain obvious errors and checked all references. The translation, wherever the reviewer took occasion to compare it with the original, is accurate and the English is very readable. The text has been brought up-to-date by the addition of numerous references and notes, some of the latter being several pages long. On page 161, an excellent chart has been added showing diagrammatically the "Reactions of the Rubber Hydrocarbon." Complete structural formulas are used wherever organic compounds are discussed. The text abounds with cross-references, and there is a very large and useful author and subject index. Furthermore, a valuable and comprehensive bibliography of all important books and pamphlets on rubber has been added. Only a very few typographical errors were noted, and these are generally minor. On page 192, the name of the journal "Rubber Chem. Tech." should be "Chemical Reviews."

This book is really what its name signifies, a treatise on "The Science of Rubber." The work is substantially complete, it is well-written, authoritative, and generally useful. HARRY L. FISHER.

Through Space and Time; by Sir JAMES JEANS. Pp. xiv, 223, 22 by 15 centimeters. The Macmillan Company, 1934 (price $3.00).—This book is based upon the Christmas lectures delivered by the author at the Royal Institution in 1933. These lectures, now become a tradition of more than a century's standing, were originally intended for a "juvenile auditory," but nowadays, as the author remarks in his preface, the audience ranges in age from eight to eighty years, and in intelligence from that of the average schoolboy to that of venerable Fellows of the Royal Society. The difficulty of keeping such an assembly interested is not small, but most of the Christmas lecturers have succeeded in doing this with surprising success. Sir James Jeans has lived up to this tradition very well, and the book before us must interest everyone who has any liking for science. The journey through time is an account of geology and that through space an account of astronomy. How well the reader is conducted on these journeys may be judged from the following quotations (from page 37): "Somewhere between these limits—1500 million and 3400 million years—the age of the earth must lie . . . . We may perhaps best visualize a million as the number of letters in a fair-sized book—a book, say, of 500 pages, with 330 words on each page, and an average of six letters to a word. If we take such a book to represent the age of the earth, then the whole of recorded human history will be represented by the last word in the book, and the whole Christian Era by less than the last letter. Within the space of this last letter the Roman Empire rose and fell; Christianity has spread over the face of the earth; the countries of Western Europe have changed from the savage countries described by Caesar to what they are to-day; more than sixty generations of men have lived and died."

The book is gotten up with an excellence worthy of its contents, the print and make-up of the page being especially pleasing.

YALE OBSERVATORY, 1935, March 6. FRANK SCHLESINGER.

Sex and Culture; by J. D. UNWIN. Pp. xxiii, 676 with tables and charts. New York, 1934 (Oxford University Press, price $12.00).—The present book brings together large amounts of evidence bearing upon a thesis presented in briefer form by the same author in 1933. (*Sexual Regulations and Human Behavior*, Williams and Norgate). According to Mr. Unwin, the cultural level of a people, as measured by their general manner of thinking, is a function of the social restraint placed upon the sexual impulse. The idea comes, of course, from the analytical psychologist's conception of sublimation. Energy not given an outlet in direct sex activity will, it is assumed, appear in other than sexual activities.

The crucial criterion of a culture, according to Mr. Unwin, is the type of interpretation which it applies in the presence of strange or striking occurrences, such as the birth of twins, sudden death, or an animal of exceptional strength or peculiar appearance. He distinguishes four levels of interpretive activity: the zoistic, manistic, deistic, and rationalistic. These types of interpretive activity require increasing amounts of energy in the order named; and the amount of this energy available is determined by the social regulation of sexual behavior imposed by a given society. Such restraints may be placed upon the prenuptial or the postnuptial life. When a people enters a period of increasing sexual control, there is an accompanying increment in the level of intellectual life, whereas a period of decreasing sexual restraints is marked by intellectual deterioration. Since Mr. Unwin recognizes that such restraints are never imposed evenly throughout a social group, he admits the possibility of considerable intellectual stratification within the group.

Evidence upon the thesis of this book is drawn from eighty uncivilized societies and from a much smaller number of civilized societies. Mr. Unwin feels, however, that anthropological data are more reliable than is the history of earlier peoples in the settlement of a question of this kind. EDWARD S. ROBINSON.

The Human Body, Its Structure and Activities and the Conditions of Its Healthy Working; by H. NEWELL MARTIN. Twelfth edition; revised by ERNEST G. MARTIN. Pp. xiv, 701, 167 figs. New York, 1934 (Henry Holt and Co., $4.00).—In this volume, the chief facts of physiology are marshalled in a pleasant, direct and readable style. Furthermore, sufficient background is afforded in the related sciences, anatomy, histology, or any other field—for example, physics, in the case of muscle,—to make the book adequate, yet sufficiently succinct. All fields of physiology are covered, special attention being devoted to the physiology of muscle, nerve (including special senses), circulation, respiration, digestion, reproduction and hormones.

The figures, as, for example, those illustrating the physiology of the circulation, add to the value of the book, as do the suggestions for laboratory work.

This volume will be especially useful to pre-medical students and to members of the various zoological fields who desire a deeper knowledge of the functions of the human body.

H. E. HIMWICH.

OBITUARIES.

DR. BOHUSLAD BRAUNER, professor of chemistry at the University of Prague from 1897 to 1925, died on February 15 when nearly the age of eighty.

MR. JOHN FRASER, British horticulturalist and botanist, died on January 24 at the age of eighty-one.

DR. THOMAS CRAMER HOPKINS, professor of geology and head of the department at Syracuse University for thirty-one years, died on April 3 at the age of seventy-three.

DR. CHRISTIAN HÜLSEN, the German archaeologist, died on January 19, at the age of seventy-six.

DR. GEORGE EDWIN JOHNSON, professor of zoology at the Agricultural Experiment Station, Kansas State College, died on March 28 at the age of forty-five.

DR. JOHN JAMES RICKARD MACLEOD, professor of physiology at the University of Toronto, died on March 17 at the age of fifty-eight. He was associated with Sir Frederick C. Banting in the discovery of insulin, and both shared the Nobel Prize.

SIR EDWARD SHARPEY-SCHAFER, professor emeritus of physiology at Edinburgh University, died on March 30 at the age of eighty-four.

DR. WILLIAM JOHN SINCLAIR, for thirty years a member of the geology department of the Princeton University, died on March 25 at the age of fifty-seven. He was an expert on fossils, and had directed the classification of thousands of specimens in the museum. In recent years he had been doing most of his field work in the Dakotas.

DR. AXEL WALLEN, director of the Service Météorologique et Hydrographique de Suède, died on February 24 at the age of fifty-eight.

PUBLICATIONS RECENTLY RECEIVED

Fossil Cycads, with special reference to Raumeria Reichenbackiana Goeppert Sp. of the Swinger of Dresden; by G. R. Wieland. Stuttgart, 1934 (E. Schweizerbart'sche Verlagsbuchhandlung).

Rensselaer Polytechnic Institute Bulletin. No. 50. Theory and Use of the Metallurgical Polarization Microscope; by Russell W. Dayton. Troy, New York, 1935.

The Principles of Quantum Mechanics; by P. A. M. Dirac. Second Edition, New York, 1935 (Oxford University Press, $6.00).

Hilger Catalogue F. Spectroscopic and other Accessories. London, 1934 (Adam Hilger Ltd.).

An Introductory Course in College Physics; Newton H. Black. New York, 1935 (TheMacmillan Co., $3.50).

The Structure and Properties of Matter; by Herman T. Briscoe. First Edition. New York, 1935 (McGraw-Hill Book Co., $3.75).

New York Academy of Science. Scientific Survey of Porto Rico and the Virgin Islands. Vol. XIV—Part 2. Insects of Porto Rico and the Virgin Islands—Homoptera (excepting the Sternorhynchi); Herbert Osborn.

Planetario Tascabile Hoepli (Ulrico Hoepli, Editore, Milan, Italy, 1935).

The Plant Kingdom; William H. Brown. Boston, 1935 (Ginn and Co., $3.50).

On Several Archāan Rocks from the South Coast of Norway; by W. C. Brøgger. II. The South Norwegian Hyperites and their Metamorphism. Oslo, 1935 (I Kommisjon Hos Jacob Dybwad).

Sub. No. ....
Book No. ....
LIBRARY

AMERICAN JOURNAL OF SCIENCE

JUNE 1935

MYLONITES FROM THE SAN ANDREAS FAULT ZONE.[1]

AARON CLEMENT WATERS AND CHARLES D. CAMPBELL.

INTRODUCTION.

The San Andreas Fault is one of the most striking structural features in California. The fault zone has been traced more than 500 miles within the confines of the State and extends an unknown distance on the sea floor to the northwest. It is usually described as a roughly vertical shear, although the true dip of the fault, the date at which movements along it began, its relation to other structural features of the State, and many of its other characteristics are as yet imperfectly known. The strike-slip component of the displacement is undoubtedly large and it has been suggested that it may be as much as 25 miles.[2]

Certain parts of the fault zone have been very thoroughly studied. Following the disaster of 1906 the State Earthquake Commission amassed a wealth of detailed information on the nature of the fault[3] and this information has been supplemented in the maps and text of the San Francisco Folio.[4] Noble[5] has made a detailed study of the fault in the Mohave desert region, and discussions of its relations in other areas have been published by many others.[6]

---

[1] Presented at the thirty-third meeting of the Cordilleran Section, Geological Society of America, Berkeley, 1934.

[2] Noble, L. F.: The San Andreas Rift and some other Active Faults in the Desert Region of southeastern California. Carnegie Institution Year Book No. 25, p. 420, 1925-26.
Reed, R. D.: Santa Margarita Conglomerate of the Temblor Range. Proc. Geol. Soc. Am. for 1933, p. 310. (June, 1934.)

[3] Lawson, A. C., and others: Report of the State Earthquake Investigation Commission, Carnegie Institution of Washington, Publ. No. 87, 1908.

[4] Lawson, A. C.: The San Francisco Folio, U. S. Geol. Survey, No. 193, 1914.

[5] Noble, L. F.: Op. cit., pp. 415-428.

[6] Willis, Robin: Physiography of the California Coast Ranges, Bull. Geol. Soc. Am., Vol. 36, pp. 641-678, 1925.
Reed, R. D.: The Geology of California, Tulsa, 1933.

It is the purpose of this paper to record the presence and significance of unusual cataclastic metamorphic rocks known as mylonites and ultramylonites which are associated with the fault zone.

In the preparation of this paper we have received assistance from a number of sources. Mr. Alexander Tihonrarov, Geological Technician of Stanford University, has aided us greatly by preparing an exceptionally fine series of thin sections from materials that present unusual difficulties to the section maker, and in addition his assistance with the translation of some of the more difficult passages in Russian articles dealing with mylonites has been especially valuable. Professors H. V. Taylor and O. C. Shepard gave their time and equipment to carry out the fusion tests reported in the paper. The loan of specimens or thin sections from Professors Bailey Willis, Adolph Knopf, A. F. Rogers, Howel Williams, and Dr. G. W. Crickmay is gratefully acknowledged. The expenses connected with the preparation of the manuscript and for the chemical analysis were defrayed by a grant from the Research Committee of Stanford University.

DEFINITION OF MYLONITE.

The word mylonite was first used by Lapworth (28)[7] to describe certain laminated or schistose-appearing rocks associated with thrust faults in the Eriboll district of the Northwest Highlands of Scotland. According to Lapworth, "mylonites may be described as microscopic friction breccias with fluxion texture, in which the interstitial dusty, siliceous and kaolinitic paste has only crystallized in part." The word is from the Greek meaning "mill" and Lapworth considered the pulverization of rock material along a great fault to be analogous to the milling of grain. Four conditions are implied in Lapworth's definition and subsequent discussion. First, a mylonite is a microbreccia produced by the milling down of the original rock material into an aphanitic paste which can only be resolved by the microscope; second, the rock must possess a flow structure, or lamination, as a result of the streaking out of the pulverized paste; third, the pulverization must have occurred under such conditions that the rock retains its coherence; and fourth, the rock must be characterized by cataclastic rather than crystalloblastic textures. The retention of coherence in the rock during crushing may be due not so much to the welding together of the broken particles by newly formed minerals as Lapworth emphasized, as it is to the fact that the rock was fractured under such great confining pressure that the surfaces of movement never opened widely enough to break the molecular bonds between them. By deforming rocks under strong confining pressure Adams and Bancroft (2, p. 637) have experimentally produced the mylonitic texture in rocks at room temperature without recrystallization.

---

[7] Numbers in parentheses refer to the bibliography at the end of the paper.

Since Lapworth's original work on this subject mylonites have been found in many widely separated parts of the world and an extensive literature with representative articles in at least seven different languages has grown up about them (see bibliography at the end of this paper). Many of the later workers have not adhered rigidly to Lapworth's definition and as a result the meaning of the term "mylonite" is at the present time a source of considerable confusion. In general it may be said that the majority of German, Scandinavian, and English writers have followed Lapworth's definition in considering mylonites essentially unrecrystallized, coherent, microbreccias, but some of them have not followed the qualification that the pulverized material must show fluxion structure. Quensel, who has written an excellent and widely quoted article (32) on cataclastic rocks, defines mylonites as microbreccias but recognizes two subvarieties, one of which (*mylonitschiefer*) shows a laminated structure whereas the other (*mylonite im engeren Sinn*) is an essentially directionless microbreccia. On the other hand most French workers, and notably Termier, who has written several important articles on this subject, have departed widely from the original definition. Termier uses the term mylonite in a tectonic rather than a petrographic sense to include all materials formed by crushing no matter what their nature. His point of view is well expressed in a footnote to a paper written in 1928 (38, p. 1247):

> "Comme tous les tectoniciens, nous appelons *mylonite* toute roche écrasée, quelle qu'ait été sa nature originelle et quel que soit le type de son écrasement."

In America the term mylonite has not been widely used, but even in the few articles in which it has been employed the same confusion has arisen.[8] Which of these various meanings will eventually prevail only usage will determine. It has seemed to us that there should be no middle ground and that either the original rigid definition of Lapworth should be adhered to or else the term should be greatly broadened and used in a tectonic sense as Termier has done. The inclusive terms "fault breccia" and "cataclastic rock"[9] are available for tectonic usage, and Grubenmann and Niggli (15, pp. 221-222) have proposed the name "cataclasite" for those microbreccias which do not show fluxion structure. On the other hand no other term adequately fills the place Lapworth assigned to mylonite. To us it seems desirable to retain the original meaning proposed by Lapworth, and this course has been followed throughout this paper.

RELATIONS OF MYLONITES TO OTHER ROCKS.

Mylonites are transitional into a great many different kinds of rocks. By decrease in the degree of coherence they grade into ordinary gouge and finely pulverized fault breccia. By decrease in the degree of crushing they grade into megascopic, coherent breccias to which various names have been applied, and these breccias grade in turn into uncrushed rocks of all kinds. By increase in the degree of recrystallization mylonites grade over into either the progressive or retrogressive (27) varieties of crystalline schists. In some localities (3, 4, 12, 16, 18, 20, 22, 23) it is believed that the temperature generated by friction during fault movements has been sufficient to fuse the mylonite paste to a glass. These fused products have been called "pseudotachylyte" (35) and "flinty crush-rocks," and all transitions are assumed to exist between them and mylonites. More or less elaborate classifications of cataclastic rocks that take into account one or more of these methods of gradation have been proposed by Termier and Boussac (37), Staub (36), Quensel (32), Raguin (33), Shand (35), and others. Most of these classifications do not consider all of the possible gradations because of the fact that each was designed to fit the rocks of a specific area in which not all of the different gradations occur. Many writers, instead of introducing new terms, have preferred to use descriptive phrases such as "fissured and brecciated granite" (37), "mashed rock" (33), "purée parfaite" = "perfect soup" (37), in describing the various stages in these gradations.

---

[8] Cf. the usage of Crickmay (13) with that of C. L. Baker, Jour. Geol., Vol. 40, pp. 577-603, 1932.

[9] Holmquist (21) uses "cataclastic" rock as a synonym for mylonite, but nearly all other authors have used it in a much broader sense.

In the glossary below definitions of the more important names in use for cataclastic metamorphic rocks are given. The reader is also referred to the list of definitions given by Quensel (32, pp. 99-100), and by Mrs. E. B. Knopf (27, p. 13). It should be strongly emphasized, as pointed out in the glossary, that there is not universal agreement regarding the meaning of some of these terms. There has also been much duplication in naming. In most cases the relatively few terms listed in the chart in Table I will adequately cover the different varieties of cataclastic rocks that may be encountered.

GLOSSARY.

AUGEN SCHIST.—*Lapworth, 1885.* A rock intermediate between a mylonite and a crystalline schist. The "augen" are porphyroclasts and preserve evidence of cataclastic structure, but the surrounding ground-mass has been recrystallized. Augen schist is the equivalent of mylonite gneiss but is not as thoroughly recrystallized as blastomylonite.

BLASTOMYLONITE.—*Sander, 1912.* A crystalline schist which shows traces of cataclastic structure only very faintly. Augen are common but they have been largely or entirely recrystallized and can only be recognized with great difficulty. The rock represents a more advanced stage of recrystallization than that shown by augen schist or by mylonite gneiss.

CATACLASITE.—*Grubenmann and Niggli.* An aphanitic, structureless cataclastic rock. Differs from mylonite (Lapworth) in the absence of fluxion structure.

FLINTY CRUSH-ROCK.—*Clough.* A dark-colored flinty, or quartzite-like rock found as veins and stringers adjacent to fault zones, and formed by ultracrushing and perhaps partial fusion of the finely comminuted rock powder along the fault. See also ultramylonite, pseudotachylyte, purée parfaite.

GANGMYLONITE (OR DIKE-MYLONITE).—*Hammer, 1914.* An ultramylonite or mylonite which shows intrusive relations to the adjacent rock. Differs from pseudotachylyte in the absence of evidence of fusion, the pseudointrusive habit of the material being due to flowage of the crushed rock powder during cataclasis instead of to the intrusion of a melt.

HARTSCHIEFER.—A name first used by Swedish geologists for strongly banded aphanitic or flint-like rocks of obscure origin associated with mylonites. Under the microscope they show a combination of cataclastic and crystalloblastic textures. There has been much difference of opinion as to their origin, Holmquist (21) even favoring the idea that they are sedimentary rocks. In the opinion of most Swedish geologists they differ from ultramylonite, which they resemble rather closely, in the remarkable banding, a feature that is regarded to be the result of metamorphic differentiation, and in the much more thorough recrystallization, crystalloblastic structures commonly predominating over cataclastic.

KAKIRITE.—*Svenonius.* In describing the cataclastic rocks of the Lake Kakir area Svenonius appears to have included under this term rocks that would now be called mylonites as well as more coarsely sheared and brecciated materials, and perhaps some rocks that would be called hartschiefer. Later workers have interpreted the term in different ways. Holmquist (21) regards the term kakirite to be synonymous with mylonite (in Lapworth's sense). Quensel (32), however, considers kakirite to be "a megascopically sheared and brecciated rock in which the fragments of the original material are surrounded by innumerable gliding surfaces in which intense granulation and some recrystallization has taken place." This definition of the term would make it practically synonymous with the very appropriate term "protomylonite" which Backlund (5) has suggested for megascopically brecciated cataclastic rocks.

MYLONITE.—*Lapworth, 1885.* (See that part of this article entitled "Definition of Mylonite.") A coherent, aphanitic, cataclastic metamorphic rock, with fluxion structure, which has been formed by the milling down of rock material to a microscopic breccia as a result of movements along a fault. Cataclastic structure predominates over structures due to recrystallization. Commonly a few porphyroclasts of incompletely crushed material are enclosed in the aphanitic paste. As stated elsewhere in this article the term has been used in widely varying senses by different workers.

MYLONITE GNEISS.—*Quensel, 1916.* A rock intermediate between a mylonite and a crystalline schist, the texture being a combination of cataclastic and crystalloblastic elements. Augen structure is very characteristic, the augen commonly consisting of crushed aggregates of felsic minerals set in a recrystallized matrix containing a greater proportion of ferromagnesian constituents. Equivalent to the "augen schist" of Lapworth.

MYLONITSCHIEFER.—*Quensel, 1916.* This term is synonymous with mylonite (in Lapworth's sense). Quensel used the term to separate laminated mylonites (*mylonitschiefer*) from homogeneous unlaminated cataclastic rocks (*mylonite im engeren Sinn*). The "*mylonite im engeren Sinn*" is the same as the "cataclasite" of Grubenmann and Niggli.

PROTOMYLONITE.—*Backlund, 1918.* A coherent crush breccia made of megascopically visible particles which are commonly lenticular in shape and which preserve faintly the primary structures (stratification, schistosity) of the original rock. Resembles conglomerate or arkose on weathered surfaces. Commonly shows innumerable megascopic gliding surfaces. Equivalent to kakirite (as defined by Quensel), to the "nodular mylonite" of Raguin, and to the "fissured and brecciated granite" of Termier and Boussac.

Unfortunately Holmes (The Nomenclature of Petrology, p. 190) has defined protomylonite as "a mylonitic rock produced from contact metamorphic rocks, granulation and flowage being due to overthrusts following, in the first place, the contact surfaces between the intrusion and the country rock." Although the type protomylonite from Cape Chelyuskin-Sarya on the north tip of Asia has been formed by the brecciation of a banded hornfels it seems evident to the writers from Backlund's description that he intended the term to have wider application than indicated by Holmes. Backlund clearly emphasizes the coarse brecciation, pointing out the resemblance of the rock to conglomerate, and implying in the prefix "proto" that the rock is first in a series of rocks of which mylonite and ultramylonite are representatives.

PSEUDOTACHYLYTE.—*Shand, 1914.* A dark-colored rock of vein-like or pseudo-intrusive habit which bears a strong resemblance to tachylyte, but which has been formed by the local fusion of finely granulated rock powder, and is not attributable to igneous agencies. Differs from most flinty crush-rock in having undergone more thorough fusion, and in being less clearly related to definite fault surfaces. See also ultramylonite, gangmylonite, purée parfaite.

PURÉE PARFAITE.—*Termier and Boussac, 1911.* A microbreccia consisting of particles that have been so finely crushed that the rock resembles chert, or phonolite, or a sort of hard greenish wax. The fracture is scaly, almost homogeneous.

TABLE I.

Cataclastic Rocks and the Processes Concerned in their Origin.

DOMINANT PROCESS			
CRUSHING		RECRYSTALLIZATION	FUSION
Near Surface (Material incoherent or cemented by later secondary processes: Pressure and temperature low.)	*At Depth* (Material remains coherent throughout ruptural deformation. Pressure moderate or strong, temperature low.)	(Ruptural deformation occurs under sufficient pressure and at a high enough temperature to bring about extensive recrystallization.)	(Temperature during deformation high enough to result in partial or complete fusion.)
GOUGE, and finely pulverized fault breccia	ULTRAMYLONITE Some FLINTY CRUSH-ROCK	HARTSCHIEFER	PSEUDOTACHYLYTE Some FLINTY CRUSH-ROCK
	MYLONITE	BLASTOMYLONITE	
		MYLONITE GNEISS	
FAULT BRECCIA	PROTOMYLONITE		

Increase in grain size ↓

Increase in temperature and pressure →

Equivalent to ultramylonite. See also flinty crush-rock, pseudotachylyte.

ULTRAMYLONITE.—*Staub, 1915; Quensel, 1916.* An ultra crushed cataclastic rock in which all porphyroclasts have been demolished to breccia streaks and the last relics of the original structure have disappeared, thus producing a homogeneous aphanitic rock of cherty, felsitic, or quartzitic appearance. Equivalent to purée parfaite. Differs from flinty crush-rock and pseudotachylyte in the absence of evidence of fusion.

COMPLEX MYLONITIC ASSEMBLAGES.

At many localities several different varieties of cataclastic rocks occur together forming mapable units which range up to more than 1,000 feet in thickness and which can be traced along the strike for many miles. In Sierra Baias, south of Buenos Aires, a band of quartzitic-appearing mylonite derived from gray granite is reported to be 100 meters thick (6). Demay (14) reports a similar 100 meter band of mylonite derived from gneiss in the Pyrenees. In the Torneträsk region of Swedish Lapland a belt of mylonites and associated hartschiefer reaches a thickness of 300 meters (21). A much more complex unit in which many kinds of cataclastic rocks showing varying degrees of crushing and recrystallization are especially prominent is the "*protogine*" of the Alps (29). In Corsica Termier and Maury (38) report a complex band of crushed rocks reaching the amazing thickness of 24 kilometers, and similar relations are stated by Termier to hold in the Island of Elba, although from a review of the field relations and on the basis of chemical analyses Aloisi (1) has seriously questioned Termier's conclusions regarding Elba. The association of mylonites with zones of "*diaphthorites*," or retrogressive metamorphic rocks, has recently been emphasized by Mrs. E. B. Knopf (27). O. O. Backlund (6) gives an interesting discussion of some of the thicker mylonitic units that have been described and points out the confusion that arose in some regions through mistaking these bands of cataclastic rock for stratigraphic rather than tectonic horizons. This danger is especially great because true mylonites have a very deceptive appearance and it is seldom possible to establish their nature without the aid of the microscope. In hand specimens they may bear a very close resemblance to slate, phyllite, altered banded lava, quartzite, graywacke, chert, and other kinds of rock.

FIELD RELATIONS OF THE SAN ANDREAS MYLONITES.

Detailed mapping in various parts of California has emphasized the fact that the San Andreas should be thought of not as a single fault surface, but as an intricate group of anastomosing fractures occupying a belt that is commonly more than half a mile wide. The rocks along this zone are much sheared and broken, and fragments derived from every formation in the region from the oldest to the youngest have been brought together in a chaotic jumble. At some localities these blocks are sufficiently large to be mapped as separate fault slivers, but elsewhere they have been ground down until the entire zone can be designated only as a heterogeneous fault breccia. One mass of breccia of this sort occupies the fault zone in the vicinity of Crystal Springs Lakes and the character of the material is well displayed in a long road-cut on the Skyline Boulevard at a locality about one-half mile (measured along the road) southwest of the point where the boulevard crosses the lake (Locality 1, Fig. 1). A great number of different rock varieties are found in this breccia, but the most common ones are serpentine, feldspathic sandstone and siltstone, altered basalt or diabase, quartz diorite and diorite, quartzite, graywacke, impure calcareous rocks, and a well-laminated black rock with aphanitic texture which the microscope shows to be a true mylonite. Many of these rock varieties have clearly been derived from the heterogeneous Franciscan series[10] which crops out extensively in the immediate vicinity, but the parentage of many of the fragments is more obscure. The dark-colored, aphanitic mylonite is the most abundant constituent of the breccia. Megascopically it resembles a slate or phyllite, but the microscope immediately reveals its cataclastic nature. Similar mylonites crop out at another locality (Locality 2, Fig. 1) near the the north end of Crystal Springs Lakes, but the material from this place is not so favorable for microscopic study because hydrothermal action has introduced large amounts of carbonate into the rock subsequent to mylonitization. The exposures between these two localities are very poor, most of the fault zone being occupied by the lake or covered over with a thick mantle of soil. In this soil, however, fragments of mylonitic rock are common.

---

[10] Lawson, A. C.: The San Francisco Folio, U. S. Geol. Survey, No. 193, 1914.

Branner, J. C., Newsom, J. F., and Arnold, Ralph: The Santa Cruz Folio, U. S. Geol. Survey, No. 163, 1909.

Unlike the other rock varieties of the fault breccia, the mylonite occurs not in distinct blocks but as a sort of matrix which encloses the other rock varieties. Locally it forms great tabular masses many feet in thickness. It grades into all the other rock varieties and in this transition gradually takes on the properties and appearance of the rock with which it is in contact. Thus adjacent to the altered basalt the

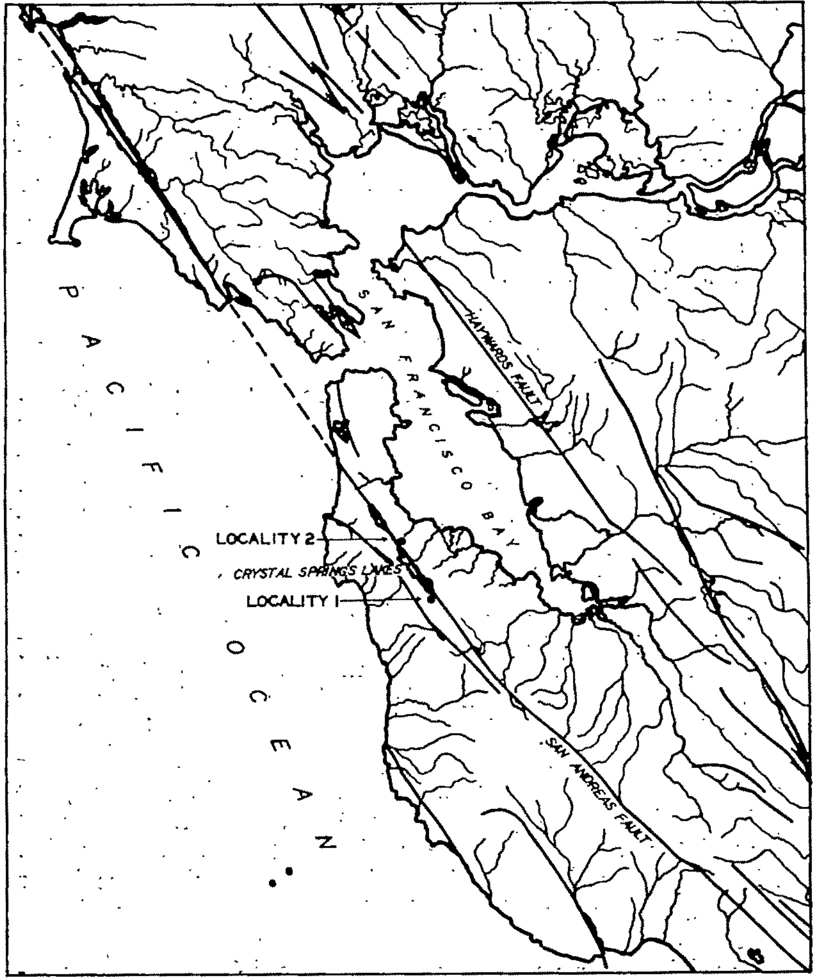


Fig. 1. Map of San Francisco Bay Region Showing Major Faults and the Position of the Two Mylonite Localities.

normally black color of the myloni green until the rock is indistinguishab tized basalt. Or it may grade into sandstone by a gradual increase in taneous decrease in the degree of lam tions are shown against quartz diorit is an even alternation of black mylon orite schist, the individual layers loc an inch in thickness. At some places ramify through the rock, some of the tion, others cutting across it at all an exceptionally well developed and p similar to that of slate or phyllite. T tion is highly variable. At Locality the fault zone and dips vertically appear. At Locality 1 both strike an although the strike is prevailingly in t of the fault, and the dip is com Although the lamination is straight a highly contorted, the folds ranging i scopic dimensions to structures a few Many faults of small displacement ar cated zones. At one place the rock s structures, one dipping at a low a practically vertically. The rock split along either of these. Another curio tion is the presence in the rock of mi out parallel with the lamination. T spots is seldom recognizable to the hand lens one can see that they are e gates, or porphyroclasts, which hav pulverization of the groundmass, an a miniature scale of the "augen" in Although the rock cleaves into thin pl phyllite, the eye-shaped spots, local co ularities cause the lamination to res of an acidic lava as much as it does morphic rock. The lustre of the ro or may be subvitreous like chert or ta

MICROSCOPIC CHAR

Under the microscope every stag original coarse grained rocks to an u be seen. Various stages in the crushing of the coarse grained Franciscan graywackes and quartzites are shown in Figs. 2 to 7 and a conception of the nature of the process may be

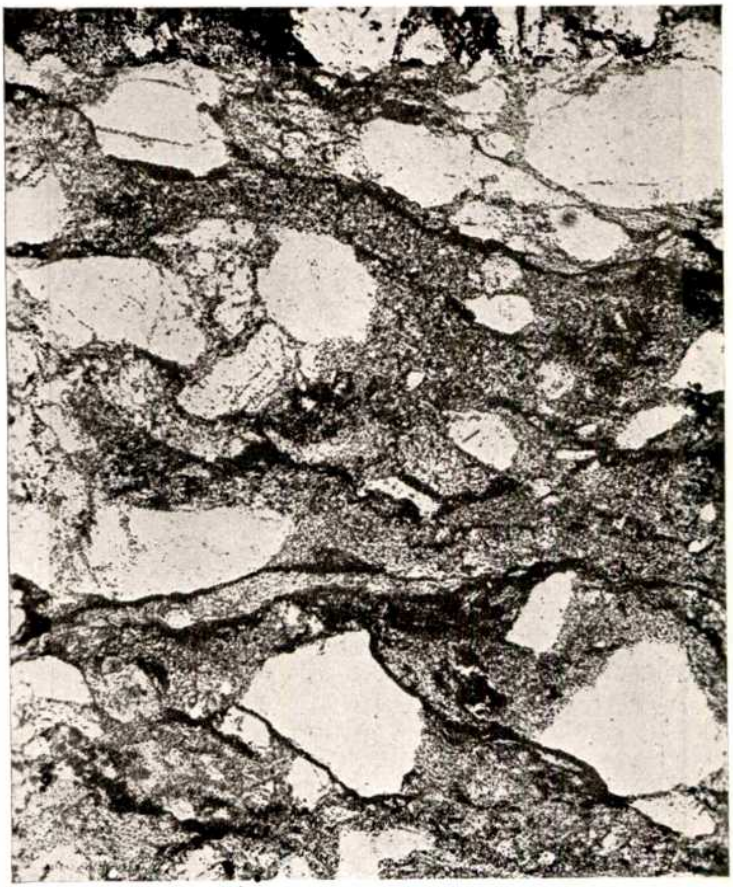


Fig. 2. Photomicrograph of a mylonite with many porphyroclasts. This rock was originally an arkose. About one-third of the original grains survive as porphyroclasts, the rest having been crushed to a microscopic powder. Crystal Springs Lakes, California (Nicols uncrossed, x 25).

more readily won from a study of the photomicrographs than from description. In general, crushing begins by the fracturing of the rock into a coherent breccia or protomylonite whose fragments are megascopically visible. Pronounced strain shadows appear in the quartz even though little shearing is visible in thin section. Further movement results in the formation of a thin film of crush powder between the mineral grains forming typical "mortar structure." The next stage is the development of a closely spaced series of microscopic shears in the individual mineral grains. With further crushing, films of pulverized material form along the microscopic shears and grow at the expense of the mineral grains until finally the uncrushed material between adjacent shears is isolated as streaks, lenticles, and irregular masses in the powdery groundmass (Figs. 2, 4). Complete rolling out of the rock to an ultramicroscopic powder in which none of the eye-shaped

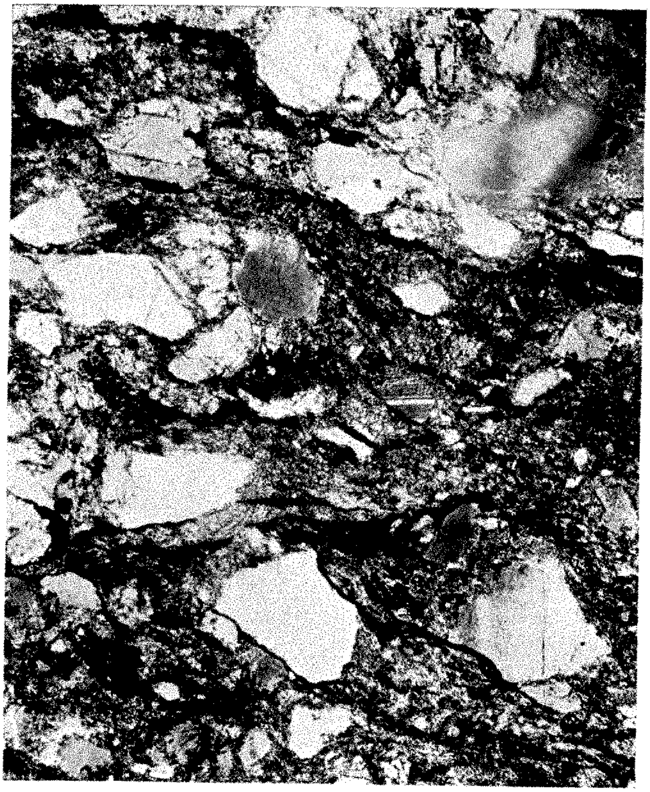


Fig. 3. The same view as Figure 2 under crossed nicols. Note strain shadows in quartz porphyroclasts.

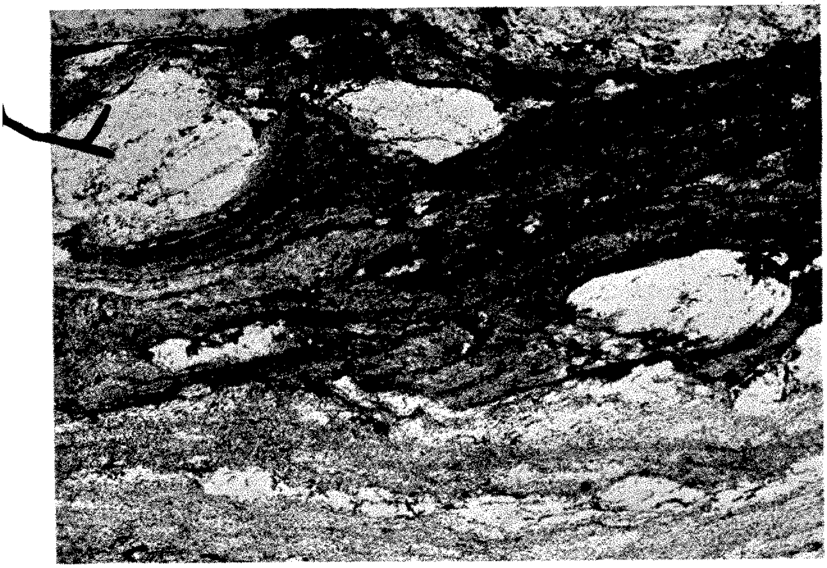


Fig. 4. Photomicrograph of a mylonite with a strongly fluidal groundmass containing a few partially rounded porphyroclasts. Crystal Springs Lakes, California (Nicols uncrossed, x 60).

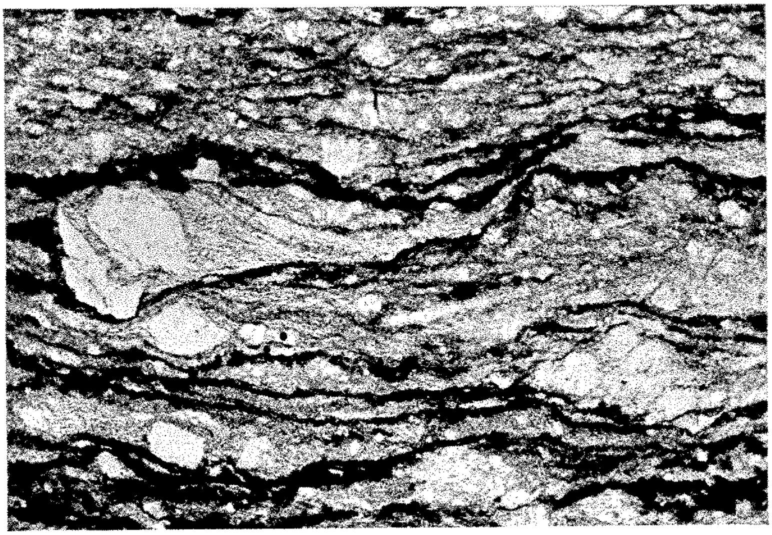


Fig. 5. Photomicrograph of mylonite with well-developed fluxion structure. Note trail of crushed particles to the right of the largest porphyroclast (Nicols uncrossed, x 80).

porphyroclasts are left is rare. The small round particles resist further milling to an unusual degree and even in those cases where the groundmass has been reduced to such small fragments that it becomes practically isotropic some of the porphyroclasts commonly survive (Fig. 6). Feldspar seems to be more resistant to crushing than quartz, as shown by the fact that feldspar porphyroclasts are relatively more abundant in the more completely pulverized mylonites.

Reduction of the material to an ultramylonitic stage in which the groundmass particles are not definitely resolvable under the microscope is more common in the brittle quartz-rich rocks than in those having an abundance of mafic minerals. The ease with which the ferromagnesian constituents transform by recrystallization results in the development of a chlorite-rich, partially crystalloblastic base before the feldspars are completely reduced to powder.

In all of the mylonites there has been at least some recrystallization of the powdery groundmass, although in the mylonitized quartzites the newly formed minerals make up less than one per cent of the total composition of the rock. The principal new mineral is chlorite, which is practically ubiquitous to all of the mylonites no matter what the nature of the original rock they were derived from. In mylonitized quartzites and graywackes the chlorite is not abundant and is a pale-colored variety with weak pleochroism and very low birefringence. It occurs in little plates that are aligned parallel with the flow structure of the rock so that in thin sections cut at right angles to the flow planes the chlorite appears as tiny rods that bear a strong superficial resemblance to the microlites of a volcanic rock, and this resemblance is especially pronounced in those mylonites having an isotropic groundmass. In a few specimens chlorite forms spherulitic aggregates. In mylonitized diabases and basalts chlorite is very abundant, and in some specimens makes up more than half of the groundmass thus forming a rock which is transitional between a mylonite and a chlorite schist. As in the graywackes the chlorite plates are aligned parallel to the flow structure and they wrap around the feldspar porphyroclasts. In the diabases the chlorite is the normal strongly pleochroic greenish variety with anomalous Berlin blue interference colors.

The marked influence of the original chemical composition and physical properties of the rock in determining the nature of the product that will be developed by deep-seated movement along fault surfaces is well brought out in these rocks from the San Andreas zone. Although serpentine is one of the most abundant rocks in the vicinity, no serpentine mylonites have been found. However, antigorite schists are interwoven in the most intricate manner with almost entirely unrecrystallized mylonites derived from graywackes and quartzite, and with partially recrystallized diabase mylonites. Evidently under the pressure-temperature conditions that result in the formation of a mylonite from quartzite or graywacke, basalts and diabases are partially recrystallized, and serpentine is entirely recrystallized and converted into schist.

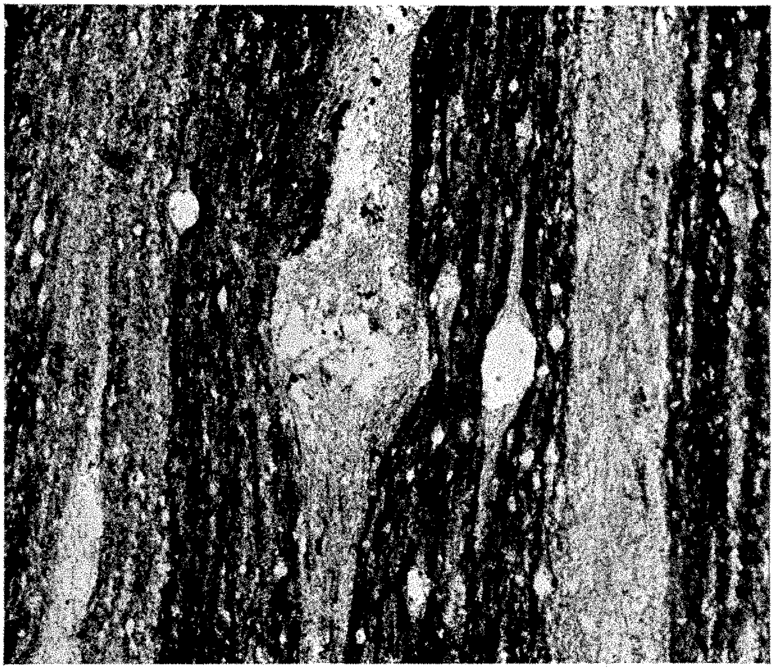


Fig. 6. Photomicrograph of ultramylonite, Crystal Springs Lakes, California. Note well-developed banding and the rounded character of the few surviving porphyroclasts (Nicols uncrossed, x 80).

Minute scales of pale-colored biotite appear in some specimens in place of chlorite. The biotite seems to be very similar to that of the Alsatian mylonites studied by Jung (26) and to that in Argentine mylonites described by O. O. Backlund (6). In a few specimens very minute irregular masses of feldspar have developed. Because of the small size of the crystals the feldspar has not been precisely identified. Although commonly untwinned it locally shows a faint polysynthetic twinning, and because of this feature coupled with its low indices of refraction it is probably albite.

Next to chlorite the most abundant mineral of new formation is quartz. The new quartz appears in two different ways. In some of the mylonites there are thin light-colored bands lying parallel with the foliation and consisting largely of quartz. Unlike the adjacent dark-colored bands these quartzose layers are characterized more by crystalloblastic textures than by cataclastic. The minute quartz grains show sutured boundaries against one another, although the effects of cataclasis can also be seen. In their peculiar combination of cataclastic and crystalloblastic textures these quartz rich bands bear a strong resemblance to the "hartschiefer" of Swedish

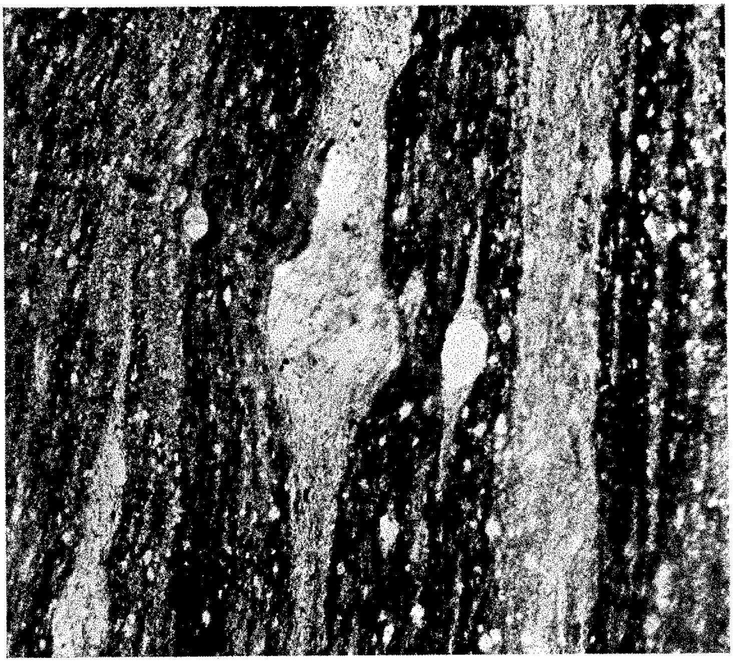


Fig. 7. The same view as Figure 6 under crossed nicols. Note the apparently isotropic character of some of the bands.

nd about the origin of which there has been considerable ence of opinion. Quensel (32) regards "hartschiefer" tially recrystallized ultramylonites which have undergone strong chemical changes during crushing and recrystallization so as to bring about marked chemical differences between the different bands.[11] On the possibility of such chemical changes during mylonitization very little is definitely known, although the question has received the attention of several writers (8, 10, 31, 32, 36, 39). In the case of a Patagonian quartz porphyry some chemical change during mylonitization is demonstrated by chemical analyses (31), although in the majority of regions the close correspondence in the analyses of the crushed rocks and the parent rocks from which they were derived is noteworthy (16, 18). If chemical differentiation of material during mylonitization does take place, it may well be that the rocks from the San Andreas fault zone showing these peculiar layers of quartz rich material represent an early stage in the transformation of a crushed rock to a chemically differentiated "hartschiefer." On the other hand it appears more probable to the writers that they represent small veinlets of quartz introduced into the rock by solutions during an early stage of mylonitization and then partially crushed as mylonitization continued. Still another possibility is that these bands may represent smears from the ultrapulverization and partial recrystallization of large quartz porphyroclasts which were reduced to powder during the last stages of mylonitization, but which were not intimately mixed with the other constituents of the groundmass. This last hypothesis encounters difficulties in explaining the more thorough recrystallization of these streaks than the rest of the rock, however. Mylonitized quartzites in the San Andreas fault zone show less recrystallization than any of the other rocks.

The second way in which new quartz appears is as definite veinlets and irregular masses that fill fractures in the mylonite (Fig. 8). The veinlets follow and also cut across the foliation. The quartz has been obviously introduced by solutions either at a very late stage of mylonitization or entirely subsequent to it. At Locality 2 (Fig. 1) considerable amounts

---

[11] On the other hand Holmquist (21) although emphasizing the difficulty of reaching a definite conclusion as to their origin, inclines to the opinion that the hartschiefer of the Torneträsk region are sedimentary, despite the fact that in an earlier paper he had considered them to be cataclastic metamorphic rocks.

of carbonates have been introduced into the rock by sol
subsequent to mylonitization, and now appear both as fr
fillings and as replacements of the groundmass of the roc

ULTRAMYLONITES WITH AN ISOTROPIC GROUNDMASS.

A few of the specimens of mylonite, and especially some of the specimens of ultramylonite in which granulation has progressed to the stage where all porphyroclasts have disappeared, show a groundmass that is partially isotropic. Commonly the isotropic part occurs in bands or layers which lie parallel with the foliation and fade off gradually into layers with a submicroscopic granular appearance (Fig. 7). The isotropic portion shows good flow structure and in some respects resembles volcanic glass. However, without crossed nicols it can be seen that this isotropic material is so crowded with impurities of various sorts as to render it nearly opaque in thin slivers, and to give it a very cloudy appearance in

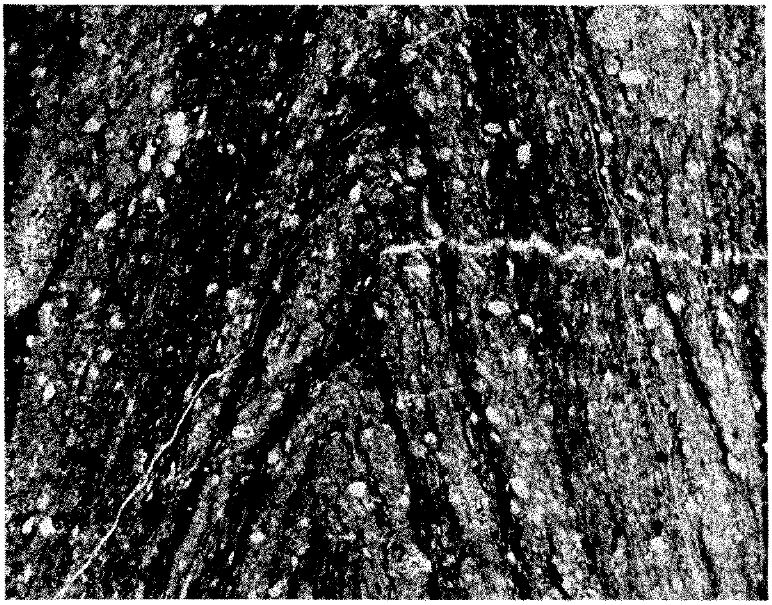


Fig. 8. Photomicrograph showing folded flow bands in ultramylonite. Note the secondary quartz veinlets cutting the flow structure. Crystal Springs Lakes, California (Nicols uncrossed, x 60).

thin section. It is also crowded with larger, although still very minute, mineral fragments similar to those in the adjacent crush bands. Probably on account of these numerous inclusions the luster, though subvitreous, is rather dull and the material resembles tachylyte, the variety of basalt glass in which there has been considerable crystallization of the iron ores,[12] more than it does obsidian. Rocks of similar nature are widespread in the Vredefort Mountain Land of South Africa where they occur as dikelike bodies ramifying through nearly all of the formations of the region. The South African geologists believe them to have been molten and apply to them the name "pseudotachylyte" (35) because of their resemblance to basalt glass. They may be of any composition depending upon the nature of the rock they were derived from. In their admirable article on Vredefort Dome, Hall and Molengraaff point out the great mechanical stresses necessary for the uplift of the dome and state (16, p. 97):

"The heating effect of this extraordinary mechanical work has been very great and in places it was great enough to raise the temperature of the triturated rocks above their fusion point. The fused rocks solidified again as pseudo-tachylyte, which thus becomes a true flinty crush-rock." The fact that the pseudotachylyte locally occurs as vein-like injections into rocks that show little evidence of crushing is explained by them as follows (16, p. 111): "in this case the fusion was complete enough to allow the molten rock to flow into cracks and finally to solidify and crystallize at a distance from its place of origin outside the crush-zones, thus forming veins in a country-rock which does not show many signs of crushing, if any . . . the great majority of rocks in the Vredefort area, invaded by pseudo-tachylyte, show more or less marked cataclastic structures, and the cases where the effects of crush are absent near the veins, can be explained by the pseudo-tachylyte having been formed from crushed rocks at some distance, but travelling towards and penetrating fissures and cracks in the non-crushed rocks, in which it is now found solidified." With regard to the solidification of the material they state (p. 98): "In the case of rapid cooling it would solidify as a vitreous or semi-vitreous rock; cooling somewhat more slowly crystallites or spherulites would develop in the groundmass; cooling still more slowly larger phenocrysts might crystallize in a denser groundmass, and rocks resembling lavas such as e.g. basalts, might be formed."

---

[12] Peacock, M. A.: The Petrology of Iceland: Part I.—The Basic Tuffs, Trans. Roy. Soc. Edinburgh, Vol. 55, No. 3, 1926.

Peacock, M. A., and Fuller, R. E.: Chlorophaeite, Sideromelane and Palagonite from the Columbia River Plateau, Am. Mineralogist, Vol. 13, 360-384, 1928.

"Flinty crush-rocks," which are similar in appearance to the pseudotachylyte of South Africa, and to which the same origin has been attributed have long been known in association with the thrust faults in the Northwest Highlands of Scotland (11, 22, 23, 30), and along the ring fault at Glen Coe (12, pp. 629-631). Especially interesting examples have been described by Jehu and Craig from the outer Hebrides (22, 23). The material is stated to be dark-colored and vitreous and it forms a sort of pavement along the thrust plane from which tongues and stringers pass down more or less vertically into the underying rock (p. 432). According to these authors (p. 436), "The association of flinty-crush phenomena with belts of shearing and movement and the independence of the pseudo-tachylytic material of any connection with extrusive rocks in the field, together with its behavior as seen in hand specimens and in microscopic sections, leave no doubt in the mind of the observer that these peculiar rocks are the product of mechanical stresses which at places have raised the temperature to an extent sufficient to bring about partial fusion of the crushed gneisses." Rocks of similar nature have been found in the Eastern Alps (3, 18) and according to Holland (20) the "trap" in the "trap-shotten gneiss" of India is also of this character. Backlund (4) suggests fusion as a possible explanation of black cherty crush rocks derived from the red and gray granites near Buenos Aires. Hall and Molengraaff (16, p. 110) regard the "*purée parfaite*" of Termier and Boussac (37) and the "ultramylonite" of Quensel (32) to be the same as flinty crush-rock although fusion was not admitted by the authors of those terms. They also suggest on the basis of a comparison of photographs that the cataclastic rocks of the Torneträsk region described by Holmquist (21) are of this nature. In a recent paper Crickmay (13) describes vitreous-appearing crush-rocks from Georgia which show marked pseudo-eruptive relations, penetrating the gneisses from which they were derived in simple and branched dike-like forms. Regarding their origin, however, Crickmay states (13, p. 170): "the mylonite is similar to pseudo-tachylyte in being pseudo-eruptive, but there has been no fusion in its development."

Some Scottish geologists have also held the view that flinty crush-rocks are not fused.

After petrographic examination and various laboratory tests of the ultramylonites from the San Andreas fault zone, we have reached the conclusion that the apparently isotropic base of these rocks is certainly not now glass and that there is very little definite evidence favoring the view that they were ever molten. The data upon which this conclusion is based may be summarily listed:

1. *Nature of transition to normally mashed groundmass.*—The bands of isotropic material always grade off very gradually into bands of cataclastic material whose constituent particles can be resolved under the microscope. In thin section it is impossible to tell where one ends and the other begins (Fig. 7). Portions that appear isotropic and homogeneous under a magnification of 250 diameters can be seen to be micro-cataclastic in many cases when the magnification is doubled. In many specimens the homogeneous appearance that is so suggestive of glass completely disappears under the oil immersion lens and the groundmass is seen to be composed largely if not entirely of very minute but yet resolvable particles. No example has been seen of the isotropic material showing sharp contacts with normally crushed material as might be expected to be the case locally if the isotropic material were molten and capable of movement at a different rate than the crushed powder it is associated with.

2. *Index of Refraction Tests.*—The index of refraction of the apparently isotropic material is somewhat variable in different specimens and may even vary slightly in the same thin section. In the specimens tested by the immersion method it is never very far from 1.56 and in all specimens examined in thin section is higher than Canada balsam. A specimen of which a chemical analysis is given in Table II, yielded semi-opaque to turbid apparently isotropic particles whose index determined by the immersion method is 1.562 ± .005. In thin section this specimen shows beautifully developed flow structure. In addition to the isotropic part (which is thickly studded with minute inclusions) there are bands that are ultra-crushed and that show a few minute, very badly pulverized porphyroclasts of quartz. The specimen also shows clear evidence of some recrystallization resulting in the formation

of tiny scales of chlorite. The chemical analysis (Table II) confirms the suggestion won from the field relations that the original rock was a slightly metamorphosed arkose, the analysis disclosing a general similarity to granodioritic rocks, but showing an enrichment of SiO_2 and of Al_2O_3 over that normal to igneous rocks of the same general composition.

TABLE II.

Chemical Analysis and Norm of Ultramylonite from San Andreas Fault Zone.

Analysis		Norm		
SiO_2	66.70%	Quartz	25.38%	
Al_2O_3	15.02	Orthoclase	10.01	
Fe_2O_3	0.83	Albite	35.63	
FeO	4.38	Anorthite	7.51	
MgO	2.64	Corundum	3.47	
CaO	1.50	Hypersthene	14.01	8.71 $FeSiO_3$ 5.30 $MgSiO_3$
Na_2O	4.20			
K_2O	1.67	Ilmenite	0.46	
TiO_2	0.20	Magnetite	1.16	
H_2O-	0.20			
H_2O+	2.60			

In the Quantitative System the rock would fall into Class II (Dosalane), Order 4 (Austrare), Rang 2 (Dacase), Subrang 4 (Dacose).
Analysis by F. Herdsman, Glasgow, Scotland.

A small portion of this specimen was heated in an oxyacetylene flame on a carbon block. It fused with evolution of some volatile matter to an extremely viscous liquid which was made into glass by quenching in water. The glass is dark greenish-gray in large pieces, but in thin slivers it is clear and shows a faint apple-green. In appearance it is very different from the unfused product and has a rather striking resemblance to sideromelane, a variety of glass formed when basalt magma is quenched by contact with water or glacial ice.[18] The index of refraction of this material, determined by the immersion method, is 1.530 ± .003, thus appreciably lower than that of the unfused material.

3. *Absence of microlites, trichites, longulites, margarites, etc.*—If the material had ever been melted by movements along the fault it seems improbable that subsequent cooling would have been so rapid that no traces of crystallization ensued. Natural glasses, unless they have been quenched by extrusion

---

[18] Peacock, M. A., and Fuller, R. E.: Chlorophaeite, Sideromelane and Palagonite from the Columbia River Plateau, Am. Mineralogist, Vol. 13, 360-384, 1928.

into water, generally show an abundance of skeletal crystal growths.[14] No crystallites have been observed in the ultramylonites from the San Andreas fault zone. In thin sections cut at right angles to the lamination, however, these rocks do show minute elongated crystals that bear a superficial resemblance to microlites. These crystals are chlorite, however, which could hardly have crystallized as a primary mineral from a melt.

4. *Comparison with fused drill-cores.*—In the process of taking cores in drilling for oil with the rotary drill several cases have been recorded where the rotation of the core barrel has developed enough friction to fuse the rock. A brief description of fused material of this sort has been given by A. F. Rogers,[15] and Bowen and Aurousseau[16] have published a longer paper giving chemical analyses and the results of various laboratory tests. Professor Rogers kindly loaned us samples of his material for examination. It bears very little resemblance to ultramylonite. The glass is clear, and has an index distinctly lower than Canada balsam, though the index is high for a silica-rich glass, perhaps due to contamination with iron from the partial fusion of the bit. In the portions in which fusion is just beginning the groundmass is darker and bears a greater, though by no means a marked resemblance to ultramylonite.

5. *Staining and etching tests.*—An attempt to detect the presence of glass by etching with hydrofluoric acid also failed.

Although these tests indicate that it is improbable that this material was ever fused, the striking similarity of the specimens as observed in thin section to the photomicrographs of pseudotachylyte in the memoir by Hall and Molengraaff (16) is very marked. Fortunately we were able to secure for direct comparison 9 specimens of pseudotachylyte from the Vredefort region. Six of these were collected by Professor Bailey Willis during an excursion of the International Geological Congress in 1928, the remaining three were collected by Professor Chester R. Longwell. These materials in thin section are so strikingly similar to the ultramylonites from the San Andreas fault zone as to leave little doubt but that the two products have had essentially the same origin. Chlorite with the same habit as that in the San Andreas mylonites was noted in some specimens, and the similarity in texture is very marked. Excellent petrographic descriptions of the South African material are given in the memoir by Hall and Molengraaff. Since the index of refraction of the materials was not given by these authors we have attempted to determine it. Many of the specimens are not isotropic, but micro-cataclastic, and much of the isotropic material is so cloudy as to be practically opaque thus rendering precise determination difficult, but in all the specimens examined the refractive index is higher than Canada balsam (1.543). A small piece of pseudotachylyte cutting granite was fused with the oxy-acetylene torch. Before fusion the refractive index, determined by the immersion method, was 1.552 ± .005. The glass formed by quenching is similar to that derived from the San Andreas rock and has a refractive index of 1.520 ± .003.

---

[14] Harker, A.: Petrology for Students, Cambridge, 150-154, 1923.

[15] Case, J. B.: Notes on the Use of the Core Barrel with Rotary Tools, Calif. Oil Fields, Calif. State Mining Bureau, Vol. 7, No. 9, 6-7, 1922.

[16] Bowen, N. L., and Aurousseau, M.: Fusion of Sedimentary Rocks in Drill Holes, Bull. Geol. Soc. Am., Vol. 34, pp. 431-448, 1923.

The abrupt drop in the index of refraction upon fusion and the presence of chlorite, would seem to indicate that glass is not now present in the rock, and that if it ever were present it must have been devitrified or altered. This throws some doubt on the conclusion that fault movements have ever resulted in the fusion of rock. The arguments that have been advanced as indicating that pseudotachylytes and flinty crush-rocks have been fused, or partially fused, are listed below. Following each title is a list of references to the original papers in which details regarding the evidence of fusion are given.

1. *Pseudo-eruptive relations.*—(3; 12, p. 630; 18; 20, pp. 198-202; 16, pp. 93-114 and plates; 22, pp. 430-436; 35). The material occurs in dike-like and vein-like masses that simulate igneous injections. The high mobility of the material is shown by its ability to penetrate minute openings (17, p. 93). This characteristic of pseudotachylyte is the one most frequently cited in support of its origin by fusion.

2. *Selvedges on pseudotachylyte dikes.*—(16, pp. 103-104). Some of the South African veins show borders or selvedges which have been interpreted as being due to changes in the rate of cooling.

3. *Resorption of inclusions.*—(3; 16, pp. 95, 100-101; 20; 22, p. 435; 23, p. 629). Quartz and other minerals are stated to be corroded by the fused groundmass.

4. *Isotropism.*—(3; 16; 18; 22, p. 436; 23, p. 629). In

the majority of cases the authors state that the isotropic material is vitreous.

5. *Presence of spherulites and of incipient crystals in the groundmass.*—(3; 16, pp. 106, 107; 18; 22, pp. 434, 436; 23, p. 629). Plagioclase is reported to occur in spherulites. In another case the spherulites are described as being "of a dark brown color in a light brown base." (22, p. 434.) The small crystals resembling microlites in the groundmass are usually too minute for precise identification but magnetite dust, plagioclase, and amphibole are reported.

6. *Experiments designed to synthesize pseudotachylyte.*—Holland (20) and Angel (3) have sintered, or partially melted, gneiss and state that they have been able to produce material similar to pseudotachylyte.

The features of pseudotachylyte listed above furnish a strong case for its origin by fusion. Nevertheless certain objections can be raised against each of these criteria. Pseudo-eruptive relations are in themselves no proof of fusion. The ability of rock to flow without undergoing either fusion or recrystallization when under strong confining pressure has long been known to field geologists and has been demonstrated experimentally by Adams and Bancroft, who state that rock deformed in this way develops typical mylonitic textures (2, p. 637). Crickmay (13, pp. 166, 170) describes clear cut examples of pseudo-eruptive relations among the mylonites of Georgia, but states specifically that the pseudo-intrusive rocks were not fused, and O. O. Backlund (6) describes very remarkable pseudo-intrusive phenomena shown by granite mylonites in Argentina. Bearth (7) has adopted Hammer's (17) term "gangmylonite" for aphanitic cataclastic rocks that bear pseudo-eruptive relations to the amphibolites and paragneisses that form the base of the Silvretta nappe in the Alps, but does not accept fusion in their production.

The isotropic character of the groundmass material suggests glass. Although several authors have definitely stated that this isotropic material is vitreous (3; 18; 16, p. 98; 22, p. 436) none of them has recorded the index of refraction of the isotropic material, or has made other physical tests useful in comparing it directly with natural and artificial glasses of the same composition. The tests that we have made indicate that the index of refraction is too high for natural glasses of the same composition, and that an abrupt drop in index occurs when the material is fused and converted into glass in the laboratory. There is very little data in the literature regarding the physical properties of the so-called glass. More definite evidence should be presented before we admit its vitreous character. In discussing isotropic crush-rocks from the East Alps Bearth (7, p. 350) says:

> "Wirkliches Glas habe ich nirgends fest-stellen können, vielmehr scheint es, als ob durch die reichliche Ausscheidung von Erz und durch die submikroskopische Dichte des Kornes der isotrope Charakter der Grundmasse nur vorgetäuscht wird."

Spherulites, although common in volcanic glasses, also develop in cherts, muds, and other fine grained materials. Spherulitic aggregates of chlorite are present in some specimens of the San Andreas mylonite and are reported to be present in the Alsatian mylonites (26). Small crystals in the groundmass of the rock that resemble microlites might be developed by metamorphic recrystallization as well as by separation from fusion.

The resorbed character of the inclusions in pseudotachylyte is undoubtedly one of the best evidences of fusion that has been presented, but even this feature is of doubtful importance. In the process of milling down a rock to an ultramicroscopic paste the few porphyroclasts that survive are likely to be well rounded. Selvedges at the borders of pseudotachylyte veins might conceivably develop due to the difference in the rate of flow of crushed material of slightly different granularity.

Although the hypothesis of fusion is attractive as an explanation of these interesting rocks, it does not seem justifiable to take too definite a position on either side of the question until more evidence has been accumulated. Careful tests should be made of the refractive index and other physical properties of the so-called vitreous material so that comparisons may be made with natural and artificial glasses of the same chemical composition. X-ray study of the material might also yield interesting results, although the abundance of minute inclusions of crystalline substances in the supposedly vitreous material would render the analysis of the results difficult. Particular effort should be made to identify correctly the minute mineral particles that have grown in the groundmass in order to ascertain whether they are the kind of minerals that would normally crystallize from a melt or whether they are those characteristically produced by metamorphic processes.

Sir George Beilby[17] proposed the hypothesis that in the polishing of metals a thin film of liquid is developed on the surface of the metal at temperatures well below the fusion point by the friction during polishing. Although this hypothesis was criticized by other chemists it has recently received strong support through experiments conducted in the Imperial College of Science laboratories.[18] R. C. Ray showed that certain changes take place in the physical properties of quartz sand which has been subjected to long continued grinding, and he interpreted these changes as being due to the conversion of some of the material into the vitreous state.[10] The material caught between moving fault surfaces must be subjected to both strong grinding and polishing action. The highly vitreous appearance of slickensides is known to all geologists. Possibly "vitreous" material produced in this way would have different physical properties from glasses of the same composition that have been produced by fusion. Jehu (24) and Hawkes (19) have already proposed the idea that the supposedly vitreous material of pseudotachylyte has been formed in this manner at temperatures well below the fusion point of the parent rock.

The simple pulverization of rock material under great confining pressure to such small size that the constituent particles are too small to be resolved under the microscope would explain the apparent isotropism of the material. This hypothesis would also best explain the refractive index of the material since the values determined are about the mean of the refractive indices of the various minerals presents. Such finely pulverized material might also be expected to have many of the physical properties of glasses, since its state of aggregation would bear many similarities to that of glass, inasmuch as recent work has indicated that the molecules in ordinary glasses are strongly polymerized. In its physical constitution such material may be transitional between the glassy and crystalline states, the individual crystalline particles being reduced to such small size that under the microscope they can no longer exert their own physical characters, the material thus becoming essentially homogeneous.

---

[17] Beilby, George: Aggregation and Flow of Solids, 79-121, London, 1921.

[18] The Deposition of Zinc on Copper, Science News, Science-Supplement, Vol. 9, No. 2050, 10, 1934.

[19] Ray, R. C.: Heat of Crystallization of Quartz, Proc. Roy. Soc., Series A, Vol. 101, No. 713, pp. 509-516, 1922; The Effect of Long Grinding on Quartz (Silver Sand), Proc. Roy. Soc., Series A, Vol. 102, No. 718, pp. 640-642, 1923.

REFERENCES CITED.

(1). Aloisi, P.: Le così dette miloniti dell' isola d'Elba, Atti della Soc. tosc. di Sci. Nat., Memorie 27, pp. 3-16, 1910.

(2). Adams, F. D., and Bancroft, J. A.: On the Amount of Internal Friction Developed in Rocks During Deformation and on Relative Plasticity of Different Types of Rocks. Jour. Geol., Vol. 25, pp. 597-637, 1917.

(3). Angel, F.: Einige neuerliche Pseudotachylyt-funde in den oesterreichischen Zentralalpen, Verh. geol. Bundensanst. Wien, pp. 143-153, 1931.

(4). Backlund, Helge: Algunas Observaciones sobre Rocas Notables provenientes de Olivarria (Buenos Aires), Dirección General de Minas, Serie B, Vol. 2, 1913.

(5). Backlund, Helge: Petrogenetische Studien an Taimyrgesteine, Geol. Fören. Stockholm Förh., Vol. 40, pp. 101-203, especially pp. 195-199. 1918.

(6). Backlund, O. O.: O Mnrohntax n Tektohntax (On Mylonites and Tectonites), Memoirs Russian Mineralogical Soc., (2), Vol. 52, pp. 145-168, 1924.

(7). Bearth, P.: Ueber Gangmylonite der Silvretta, Schweizer. Min. u. pet. Mitt., Vol. 13, pp. 347-355, 1933.

(8). Becke, F.: Fortschritte auf dem Gebiete Metamorphose, Fortschritte d. Min. usw., Vol. 5, pp. 210-264, especially pp. 234-238, 1916.

(9). Bowen, N. L., and Aurousseau, M.: Fusion of Sedimentary Rocks in Drill-Holes, Bull. Geol. Soc. Am., Vol. 34, pp. 431-448, 1923.

(10). Carstens, C. W.: Zur Frage der Genesis der Eisenerzvorkommen von Fosen, Norwegen, Zeit. prakt. Geol., Vol. 33, pp. 94-102, 1925.

(11). Clough, C. T.: The Geology of the Cheviot Hills, Mem. Geol. Surv. England and Wales, pp. 1-60, especially pp. 22-24, 1888.

(12). Clough, C. T., Maufe, H. B., and Bailey, E. B.: The Cauldron Subsidence of Glen Coe, and the Associated Igneous Phenomena, Quart. Jour. Geol. Soc., Vol. 65, pp. 611-678, especially pp. 629-631, 1909.

(13). Crickmay, G. W.: The Occurrence of Mylonites in the Crystalline Rocks of Georgia, this Journal, Vol. 26, pp. 161-177, 1933.

(14). Demay, A.: La zone mylonitique de Grimaud, et la tectonique du massif des Maures, Bull. Soc. Géol. de France, Ser. 4, Vol. 27, pp. 279-336, 1927.

(15). Grubenmann, U., and Niggli, P.: Die Gesteinsmetamorphose, pp. 219-223, 1924.

(16). Hall, A. L., and Molengraaff, G. A. F.: The Vredefort Mountain Land in the Southern Transvaal and the Northern Orange Free State, Verh. der Koninklijke Akad. van Wetenschappen te Amsterdam, (2), Vol. 24, No. 3, 1925.

(17). Hammer, W.: Das Gebiet der Bündnerschiefer im tirolischen Oberinntal, Jahrb. k. k. Geol. Reichsanstalt, Vol. 64, pp. 443-567, especially pp. 555-562, 1914.

(18). Hammer, W.: Ueber Pseudotachylyt in den Ostalpen, Jahrb. geol. Bundesanst. Wien, Vol. 80, pp. 571-585, 1930.

(19). Hawkes, L.: Pseudotachylyte, Geol. Mag., Vol. 66, pp. 143-144, 1929.

(20). Holland, T. H.: The Charnockite Series, a Group of Hypersthenic Rocks in Peninsular India, Geol. Surv. India, Memoir 28, Pt. 2, pp. 198-202, 1900.

(21). Holmquist, P. J.: Die Hochgebirgsbildungen am Torneträsk in Lappland, Internat. Geol. Cong., 11th session, Guide Book No. 6, Stockholm, 1910.

(22). Jehu, T. J., and Craig, R. M.: Geology of the Outer Hebrides, Part 1, The Barra Isles, Trans. Roy. Soc. Edinburgh, Vol. 53, pp. 419-441, especially pp. 430-436, 1925.

(23). Jehu, T. J., and Craig, R. M.: Geology of the Outer Hebrides, Part 2, South Uist and Eriskay, Trans. Roy. Soc. Edinburgh, Vol. 53, pp. 615-641, especially 629-630, 1925.

(24). Jehu, T. J.: Observations on Flinty Crush Rocks. Trans. Edinburgh Geol. Soc., Vol. 11, pp. 405-406, 1925.

(25). Jung, Jean: Sur quelques roches écrasées des Vosges, Compt. Rend., Ac. des Sci., Vol. 180, pp. 839-840, 1925.

(26). Jung, Jean: Contribution à la géologie des Vosges Hercyniennes d'Alsace, Mém. du service de la carte géologique d'Alsacae et de Lorraine, No. 2, pp. 158-171, 1928.

(27). Knopf, E. B.: Retrogressive Metamorphism and Phyllonitization, this Journal, Vol. 21, pp. 1-28, 1931.

(28). Lapworth, C.: The Highland Controversy in British Geology: its Causes, Course, and Consequences, Nature, Vol. 32, pp. 558-559; 1885; Rept. British Assoc., Aberdeen, p. 1025, 1885.

(29). Michel-Lévy, A.: Sericitoschistes des chaînes du Mont-Blanc et des Aiguilles Rouges qui sont des Mylonites recristallisées postérieures au granite, Bull. Soc. Géol. de France, Series 4, Vol. 28, pp. 255-260, 1928.

(30). Peach, B. N., Horne, J., Gunn, W., Clough, C. T., and Hinxman, L. W.: The Geologic Structure of the Northwest Highlands of Scotland, Mem. Geol. Surv. Great Britain, 1907.

(31). Quensel, Percy: Die Quarzporphyr-und Porphyroid formation in Südpatagonien und Feuerland, Bull. Geol. Inst. Upsala, Vol. 12, pp. 9-40, 1913.

(32). Quensel, Percy: Zur Kenntnis der Mylonitbildung, erläutert an material aus dem Kebnekaisegebiet, Bull. Geol. Inst. Upsala, Vol. 15, pp. 91-116, 1916.

(33). Raguin, E.: Au sujet de divers genres de "mylonites granitiques" le long des lignes de dislocation de l'Ouest du Plateau Central, Bull. des Serv. Carte Géol. de la France et des Topog., Vol. 29, No. 261, Paris, 1925.

(34). von Seidlitz, W.: Ueber Granit-mylonit und ihre tektonische Bedeutung, Geol. Rund., Vol. 1, pp. 188-197, 1910.

(35). Shand, S. J.: The Pseudotachylyte of Parijs (Orange Free State), Quart. Jour. Geol. Soc., Vol. 72, pp. 198-221, 1916.

(36). Staub, R.: Petrographische Untersuchungen im westlichen Berninagebirge, Vierteljahrsschrift d. Naturf. Gesell. im Zürich, Vol. 60, pp. 55-336, especially 71-91, 1915.

(37). Termier, P., and Boussac, J.: Sur les mylonites de la région de Savone, Compt. Rend., Ac. des Sci., Vol. 152, pp. 1550-1556, 1911.

(38). Termier, P., and Maury, E.: Nouvelles observations géologiques dans la Corse orientale: phénomènes d'écrasements et de laminage; mylonites et brèches tectoniques, Compt. Rend., Ac. des Sci., Vol. 186, pp. 1247-1251, 1928.

(39). Tröger, E.: Chemismus und provinziale Verhältnis der variskischen Gesteine Mitteldeutschlands, Neues Jahrb. f. Miner, Vol. 60, 1-110, 1929.

Stanford University,
California.

TECTONIC DISTURBANCES CONNECTED WITH PLUTONIC BODIES IN THE OSLO REGION.

OLAF HOLTEDAHL.

ABSTRACT.

From various parts of the world, where plutonic masses cut through unfolded bed rock, we know that a more or less marked basin structure, with centripetal dips, is characteristic for the surrounding area or for existing roof remains. Attention is drawn to a new example of such a basining, occurring in the Oslo region of Southern Norway, an alkaline igneous complex which is now known to be of Upper Paleozoic age.

Besides the more general basining, there occur in the district particularly dealt with, local deformations close to the igneous contact, deformations telling of a subsiding central mass of bed rock or of magma. A regular arrangement of xenoliths in the plutonic rock (a nordmarkite) is well explained upon the assumption that the fragments have dropped into the magma from the roof of the magmatic chamber.

There is finally pointed out a number of structural features that indicate a very close relation between faulting, and warping connected with faulting, on one side and the site of plutonic masses on the other. In some cases the existence of the magmatic body seems to be responsible for a subsidence of the adjacent part of the crust, in others for an uplift, an elevation which evidently is of another kind than the doming of a laccolite.

Through the discovery, in 1931, of fossils of Lower Permian age in sedimentary beds lying just below the lavas in the Asker district, a little west of Oslo,[1] we learned the rather surprising fact that the well-known suite of alkaline igneous rocks of the Oslo region belongs very high up in the Paleozoic and is not of Devonian age as previously generally assumed. A find of *Cordaites*, made in 1932 by the writer in a sandstone layer interbedded with the oldest lavas of the essexite group at Holmestrand, somewhat more to the south, and of *Walchia* by P. Störmer in 1933 in Asker, in a sandstone lying below the lowest lavas of the district, but above a lava conglomerate, are further facts of importance, as they show conclusively that the igneous activity of the Oslo region had just commenced when these Upper Paleozoic fossil-bearing sediments were deposited. Knowing how intimate are the petrological and geological relations between the various series of the Oslo eruptives, so admirably described by Brögger in a long series of papers, we can with fair safety conclude that the whole of the igneous activity of the region belongs to the Permian, probably to the oldest part of that period.

---

[1] Holtedahl, O.: Jungpaläozoische Fossilien im Oslo-Gebiete. Norsk Geologisk Tidsskrift, Vol. XII, p. 323, 1931. Heintz, A.: Fischreste aus dem Unterperm Norwegens, N. G. T., XIV, p. 176, 1934. A detailed report on the plants, by O. A. Höeg, will appear in the near future.

Thus the huge intrusions, and the imposing dislocation of the area by faulting—two phenomena no doubt closely and causally related as also emphasized by Brögger—have nothing directly to do with Caledonian orogeny, but represent an independent orogenetic phase, belonging to the Variscian (Hercynian) period. We have in the Oslo dislocations, to use Stille's term, a "germano-type" form of Upper Paleozoic orogeny, an orogeny which in its "alpino-type" facies was so characteristic a feature in regions not far away, in southwestern England, France, Germany, and in the Timan and Ural-Novaya Zemlya zones. When the igneous activity of the Oslo region started, the lava flowed over a very even plane of denudation, which cuts across the Caledonian folds. As a matter of fact we do not know of marked folds in the deposits above the plane that can be ascribed to ordinary tangential pressure of a regional kind. The dislocations, and the opening of thousands of fissures, often filled with magma in dykes of considerable thickness, represent primarily tensional movements.

During his field work, trying to trace the sedimentary zone below the lavas into other parts of the Oslo region, the writer has made certain observations along tectonic lines and has become aware of certain structural features, evidently intimately connected with the magmatic bodies. As this type of tectonics is of interest in connection with our interpretation of the mechanism of magmatic masses, a subject under lively discussion, a few statements will be given.

Even if concordant, or fairly concordant, contacts between the plutonic bodies of the Oslo region and the adjacent country rock are seen in a good many places—the large masses of syenite and granite having for considerable areas a cover of either Cambro-Silurian sediments or upper Paleozoic lavas—discordant contacts and steep boundaries are also, at other localities, a prominent feature, especially for the large massives belonging to the older series of the Oslo suite. A glance at the beautiful Brögger-Schetelig map of the Oslo region, on the scale of 1:250,000,[2] shows this very clearly. Perhaps this discordance is most evident when we trace the boundary line of the large larvikite-ekerite-mass, projecting with a marked corner far to the west in the southwestern part of the region (see Fig. 4), or the corresponding line of the nordmarkite

---

[2] Brögger, W. C.: Die Eruptivgesteine des Oslogebietes, VII. Die chemische Zusammensetzung der Eruptivgesteine des Oslogebietes. Skrifter utgitt av Det Norske Videnskaps-Akademi i Oslo. Mat.-Nat. Kl., 1933.

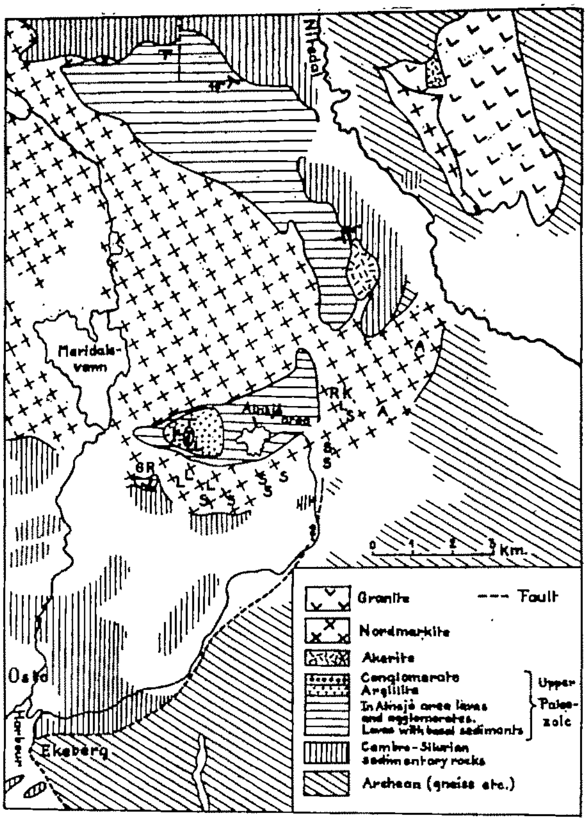


Fig. 1. Geological map of the nordmarkite-lobe northeast of Oslo with adjacent ground. Dip of Upper Paleozoic sediments shown in places. L-inclusions of lava in the nordmarkite, S-of Cambro-Silurian, A-of Archean rocks. GR-Grefsenaas, RK-Röverkollen. The northern boundary of the Alnsjö area is more irregular than shown in the map, with numerous large apophyses of nordmarkite.

massive just north and northeast of Oslo, especially the lobe between Oslo and Nitedal (Fig. 1). These intrusive masses cut in turn all the three main complexes of stratigraphically arranged rocks of the Oslo region, viz. 1. The Archean, mainly made up of gneisses; 2. The Cambro-Silurian marine sediments, with continental sandstone of Downtonian age at the top,—all folded in Caledonian time, except in the southern part of the region. 3. The Upper Paleozoic volcanic rocks, mainly lavas, with associated sedimentary beds.

In the southwestern area just mentioned another feature, that has been pointed out by various writers (Kjerulf, Brögger, Cloos), at once strikes one when looking at a detailed map; the arrangement of the Cambrian, Ordovician and Silurian sedimentary belts bordering the plutonic mass towards the Northwest and Southwest indicate a marked dip of the sediments (which here in the south are unfolded) *towards* the plutonic body. In the nordmarkite area northeast of Oslo conditions are not so easily read from the older maps, but new field investigations carried out by the writer, assisted by Mr. S. Föyn, especially during the summer 1932, have shown

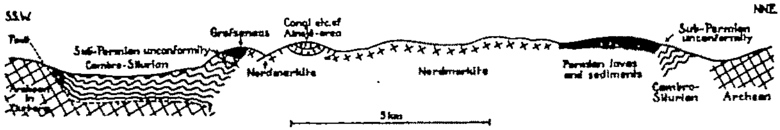


Fig. 2. Section Ekeberg-Nitedal, cp. Fig. 1.

that a similar basin-like structure is characteristic of the adjacent belt of country rock in this district also. The dips of the sub-Permian plane of unconformity, horizontal when the lavas flowed out, show how the crust has been tilted. The stratified rocks just above this unconformity also show dips in the same directions. These rocks, as in Grefsenaas Mountain just north of Oslo (GR in map Fig. 1), are (Fig 3): 1. basal beds of conglomerate, quartzitic sandstone and hornfels (shale altered through contact metamorphism), thickness 10-15 meters: 2. very fine-grained lava rock, of the essexite series, with a similar thickness: 3. quartzitic fine-grained sandstone, a few meters thick: 4. rhomb-porphyry lava, a series of considerable thickness, yet with only the basal part preserved at this locality. The general structure of the district particularly taken up for study will be seen from the map (Fig. 1), which is based on the printed (Brögger-Schetelig) Oslo maps on the scale of 1: 100,000, with additional data from the new investigations. A section is shown in Fig. 2.

The detailed structure of the country rock close to the intrusive contact in the Grefsenaas also shows interesting features, as seen in Fig. 3. On the west side of the mountain is seen in one locality (I) how the contact of the rhomb-porphyry with the underlying quartzite shows a very marked dip, much steeper than that of the basal sedimentary series which is exposed further away from the intrusive contact. At an adjacent locality conditions are as seen in II, the rhomb-porphyry-quartzite contact being here nearly vertical. However, the contact at this place is not the original stratigraphical one: the flow structure of the lava, very distinctly seen just here, is nearly at right angles to the contact. A dislocation, with a relative sinking of the rhomb-porphyry mass close to the igneous contact, has evidently taken place. On the east side of the mountain (III), where the contact dips markedly below the bed rock, one sees a very remarkable type of folding which much puzzled the writer when first he saw it. The first idea was that it might be a relatively primary feature: that the lava, while moving along above the sand-beds, had produced this folded structure. It soon became evident, however, that we were dealing with a feature of secondary origin. The rocks are in places highly crushed, clear faults being seen, also a fracturing showing a dip corresponding to that of the isoclinal folds. Further, not only lava and quartzite, but also

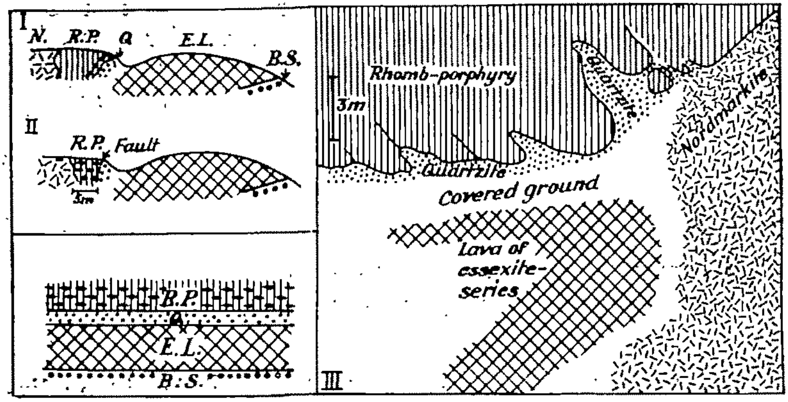


Fig. 3. Deformations of country rock close to intrusive contact in the Grefsenaas. I and II—localities near each other on the west side. Below: original stratigraphical sequence. III—locality on east side.

B.S.—basal upper Paleozoic sediments, E.L.—lava of essexite series, Q.—quartzite, R.P.—rhomb-porphyry, N.—nordmarkite, porphyritic near the contact.

the porphyritic contact-facies of the syenite seem to have been affected by the deformation. Sketch III of Fig. 3 also shows the characteristic fact that the folds become less marked and finally disappear when we move away from the syenite contact. It must, however, be emphasized that even much further away the basal few centimeters of the rhomb-porphyry bear distinct evidence of mechanical deformation of secondary character, indicating a thrusting of the lava mass above the quartzite.

Thus the secondary deformations noticed close to the intrusive contact on the Grefsenaas are of rather different type in various places; it can hardly be doubted, however, that they are all due to the same deformative forces. Of what nature were these and when were they active?

Dealing with the tectonics of the younger plutonic masses of Southwest Africa, Cloos[3] has pointed out a number of cases where the bed rock has been sharply bent down close to a plutonic body. Like Brögger[4] in his paper describing the highly interesting conditions in the contact zone of the larvikite mass near Langesund in the southern part of the Oslo region, he came to the conclusion that the deformation of the bed rock must have taken place previous to or contemporaneously with the intrusion. He also considers, for the Brandberg district, the possibility of the bed rock nearest to the igneous contact being dragged down *after* the intrusion, but finds that several facts speak against such an assumption.

Considering the conditions at the contact on the Grefsenaas, one rather natural explanation of the deformations would no doubt seem to be that the bed rock had been dragged down through a subsidence of the magmatic mass after the latter, through a peripheral chilling, had become solidly attached to the walls. Where the contact is a steep one, as on the west side, such a subsidence would effect either a bending down of adjacent bed rock, or faulting. Where the contact, as on the east side, had a marked dip below the bed rock, a downward movement of the magmatic mass, more or less parallel to the contact, would produce a dragging effect which under the existing circumstances, with the bed rock made up of layers of very different physical character, might well produce deformations just like those seen: that is, folding of a more or less isoclinal character, fracturing and thrusting. A microscopic section of a piece of rock showing the contact between the porphyritic contact rock of the nordmarkite and the quartzite of the bed rock, taken where deformations evidently have been very marked, show no clear intrusive contact, but one indicating tectonic disturbances younger than the intrusion.

---

[3] Der Brandberg. I. Geologischer Teil. Neues Jahrbuch f. Min., Geol. u. Pal. 66. Beilage Band, Abt. B, p. 50, 1931.

[4] Die Mineralien d. Syenitpegmatigänge d. südnorwegischen Augit- und Nephelin-syenite. Z. f. Kryst. u. Min., 16, p. 119, 1890.

For the previously mentioned Langesund district, however, it seems difficult to assume that the bending down of the strata of the bed rock is younger than the intrusion. The beds here are vertical near the plutonic body and there is a transitional zone with innumerable inclusions of the bed rock in the magmatic mass. In such a case it is probable, as emphasized by Cloos, "dass es gerade die Abbiegung der Sedimente war, welche ihre Fugen dem Schmelzzutritt zukehrte und öffnete und also eine so intensive und doch auf einen schmalen Gürtel scharf begrenzte Durchaderung erst ermöglichte" (l. c., p. 51). To the present writer it seems that such a marked bending down close to the igneous contact might be naturally explained if we assume the emplacement of the plutonic mass to have been brought about through a "cauldron subsidence," the bed rock close to the fracture being dragged down during the subsidence of the central body, while magma moved upwards between the bed rock and the subsiding block.

Returning once more to the structure seen on the Grefsenaas, both the bending down on the west side and the folding on the east side might be explained in a similar way, if only the syenite rock had not been affected by the deformation, as seen on the east side. Where the wall along which a subsidence takes place has an irregular surface with marked projections, a sinking mass of bed rock may well produce a pressure against the wall resulting in structures like those seen in Fig. 3, III.

As a matter of fact, the emplacement of the plutonic masses of the Oslo region, with the nicely curved, in places, even ring-like boundary lines, so well shown on the Brögger-Schetelig maps, seems to be well explained by the "cauldron subsidence" ("ring-fracture stoping") theory. It is of considerable interest that if we continue the southern boundary line of the Grefsenaas nordmarkite towards the west we pass into a ring-fault-like line of dislocation (south of C in Fig. 4) with subsidence on the north side and with a dyke of nordmarkite porphyry just at the fault, as has been noted by Schetelig.[5]

Even if, at the present moment, it is difficult to decide to what extent the deformations in the Grefsen district really are younger than the intrusions, the conditions found are of considerable interest as a new example of a general basining around a plutonic body and of very marked local deformations close to the contact.

The basin structure of this district is still more accentuated if we include the area of lavas and other supracrustal rocks which, in a West-East belt, the Alnsjö area, lie in the nordmarkite mass not far from its southern boundary (Figs. 1 and 2). These lavas no doubt belong fairly high up in the lava series of the Oslo region, above the rhomb-porphyry lava preserved in the Grefsenaas. There are also agglomerates which in places at the Alnsjö lake show a bedding of such an irregular kind that it indicates the presence of a volcanic vent in this area. Somewhat higher in the series occurs an extremely fine-grained red rock, in many places changed to black by contact metamorphism,—an argillite with possibly some tuffaceous material. Above it, as the highest zone preserved, is a conglomerate, mainly made up of volcanic rocks of various types. This conglomerate shows a well-marked synclinal structure, and at a locality near the southern boundary of this area of surface rocks, the bedding, as seen in the argillite, indicates a vertical dip.

This synclinal mass of the Alnsjö area reminds one, as to general structure and situation, of the volcanic mass of Ben Nevis in Scotland, which also is surrounded by plutonic rock, supposed to have taken the place of a sunken subterranean block of bed rock.[6]

The fact that the southern boundary of the Alnsjö mass is very sharp and regular, with a curve more or less parallel to the syenite boundary further south and southeast, favours the idea that the mass, on the southern side, has subsided along a ring fracture. On the northern side the boundary is very irregular, with innumerable apophyses of syenite cutting into the supracrustal rocks.

---

[5] Ekskursion til Bærum. Forhandlinger ved de skandinaviske naturforskeres 16. möte, i Kristiania, p. 879, 1916. See further Fig. 41 in "The Geology of Parts of Southern Norway," by A. Bugge, O. Holtedahl, C. F. Kolderup, H. Rosendahl, J. Schetelig and L. Störmer, in the Proceedings of the Geologists' Association, London, Vol. XLV, 1934.

[6] The Geology of Ben Nevis and Glen Coe. Memoirs of the Geological Survey of Scotland, 53, p. 129, 1916.

In the district particularly dealt with in this paper, that just northeast of Oslo, there are some minor features that must be regarded in any discussion of the mechanism of the intrusive plutonic masses, viz., the very numerous inclusions of country rock[7] occurring just north of the southern boundary of the nordmarkite (Fig. 1).

A study of the printed geological map of the area on the scale of 1 : 100,000 shows a somewhat regular arrangement of the inclusions; blocks of Cambro-Silurian material (generally hornfelses of various kinds) occur in more southern localities, lavas in more northern ones. As a more detailed knowledge of this arrangement is of interest, I have arranged to have a student, Mr. M. Marthinussen, carry out a revised mapping of the inclusions, the result of which will appear in map-form in another place Here it will only be emphasized that the work has strengthened the impression of a regular arrangement of the two main types of blocks; furthermore, in the extreme southeastern zone of the syenite (in which district it cuts the Archean) the existence of a large number of gneiss blocks was observed (cp. Goldschmidt, l. c. p. 40). Some very large inclusions, particularly of lava rock, occur, several of them containing a number of stratigraphical zones. I might mention a block occurring on the east side of the top of the Aarvoldsaas somewhat east of the Grefsenaas, consisting of: 1. conglomerate, quartzitic sandstone, etc. of the Upper Paleozoic basal zone; 2. essexitic lava; 3. quartzite; 4. rhomb-porphyry. Of particular interest concerning this block is that this large piece of rock has been turned about 110° from its original horizontal position. Another block with various zones occurs between the Aarvoldsaas and the Grefsenaas.

When trying to explain this arrangement of the inclusions—without applying the idea of magmatic assimilation—we at once see that if the magmatic mass had a rather convex upper part, with the contact cutting the main stratification of the country rock at an acute angle, the roof of the magmatic chamber would consist of zones of various nature, and a sinking of blocks, loosened from the roof, would result in an arrangement like that actually found. It is, then, of great interest to notice that the contact on the eastern side of the Grefsenaas has a rather gentle dip below the country rock;

---

[7] A detailed petrological study of these inclusions has been carried out by V. M. Goldschmidt, published in his well-known treatise on contact metamorphism: Die Kontaktmetamorphose im Kristianiagebiet. Videnskapsselskapets Skrifter, Mat.-Nat. Kl. p. 26, etc., 1911.

I therefore see no serious objection to explaining the arrangement in this way. Further investigations will be needed to show if similar conditions exist in other parts of the Oslo region. An interesting section of somewhat similar nature, showing a rather regular arrangement of xenoliths, with a little of the roof preserved, has been published by G. F. Loughlin from the Tintic district, Utah.[8]

If we continue the section Nitedal—Grefsen further southwards (see Fig. 2) we meet the fault-line of Ekeberg, with the Archean well exposed and the basal Cambro-Silurian shales dragged downwards along the fault plane. With the basin structure connected with the plutonic body in mind, there might seem to be a possibility that this marked dislocation may also have some close relationship to the plutonic mass considered. As a matter of fact, there is some evidence indicating that it really is so. We here touch one of the main problems of the Oslo region: the large faults and their origin. Is there, not only in a general way, but more in detail, any marked, clear connection between the faults and the site of the great intrusive masses? We notice in the northernmost part of the Oslo region very prominent faulting without any plutonic mass at all being known in the neighbourhood, and we might perhaps at once dismiss the idea of a close geographical connection. However, we must remember the possibility that there may exist a particular intrusive mass *below* an area even if we at the present time do not see it, nor its effects in contact metamorphism. We may look a little more closely at the dislocations at Oslo, at O in Fig. 4. We have in the fjord area two sunken belts, the Bundefjord and the main fjord area farther west, both tapering southwards, while they unite northwards towards the plutonic mass and the ring fracture already described. We notice how in a general way the area of main subsidence corresponds to the West-East extent of the visible part of the plutonic body to the north, and the idea lies close at hand that the breaking up and the sinking may have been directly brought about through a subsidence connected with the magmatic masses dealt with above. A main reason for the development of the tapering lobes far towards the south may be the influence of the schistosity of the pre-Cambrian basement in this area, which is mainly a North-South one. Any fault would, therefore, have a tendency to follow this direction.

---

[8] U. S. G. S. Prof. Paper 107, Pl. 5, 1919, reproduced also by Daly, "Igneous Rocks and the Depth of the Earth," fig. 101, 1933.

If there really exists so close a connection between the faulting and the site of the plutonic masses it should be possible to find somewhat parallel conditions in other parts of the region. If we follow the huge syenite mass northwestwards from Oslo we notice that it terminates towards the northwest close to the southern end of Randsfjord, the boundary here curving from a northern to a more eastern direction. Just here lies (Fig. 4) the great Randsfjord fault, also somewhat curved, ring-fracture-like and well marked, till it meets the syenite mass. We have here a feature parallel to those found near Oslo. The tilted and downfaulted area of Cambro-Silurian in Hadeland is, structurally speaking, a *parallel to the Oslo-Bundefjord area.*

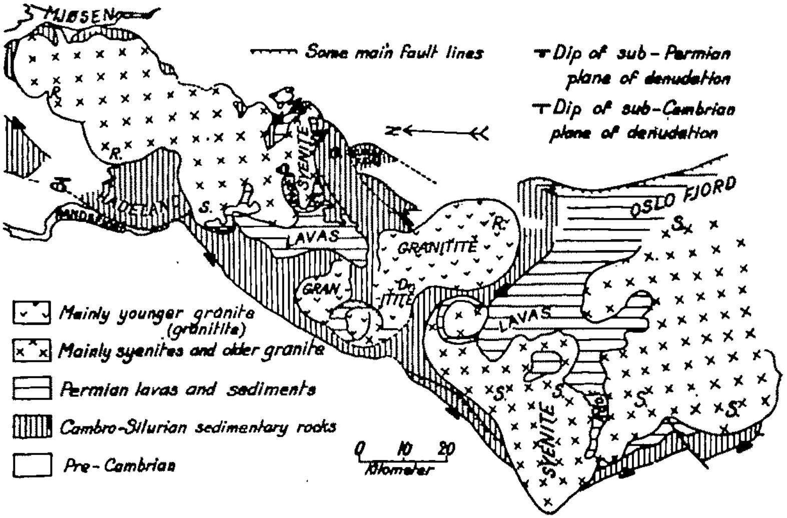

MJØSEN
Some main fault lines
Dip of sub-Permian plane of denudation
Dip of sub-Cambrian plane of denudation
R.
S.
SYENITE
LAVAS
GRANITITE
GRAN-ITE
Dr.
OSLO FJORD
SYENITE
Mainly younger granite (granitite)
Mainly syenites and older granite
Permian lavas and sediments
Cambro-Silurian sedimentary rocks
Pre-Cambrian
0 10 20
Kilometer

Fig. 4. Map showing the structural relation between the main plutonic masses of the Oslo region and some major crust deformations of adjacent districts.

S.—areas of plutonic rock where the adjacent district of country rock has subsided, R.—where it has risen, C.—sunken ring-fracture lava field somewhat west of Oslo-O. Dr.—Drammen, L.—Langesund (in the southwestern corner of the map area).

Another point must be mentioned. The fault on the north side of the Ekeberg gneiss plateau (Fig. 1) continues northeastward in a distinct curve and finally the direction of the fault line, where it approaches the nordmarkite, must be practically North-South, as far as can be judged from the few outcrops of rocks in this particular area. Further, the map shows us how the Alnsjö lava field is suddenly cut off towards the east, with a straight North-South boundary line, which markedly contrasts with the roundly triangular one to the west. Now the contact between the lava and the nordmarkite along this North-South line is one of intrusive character, and no fault. How is this to be explained? Is there any connection between the two North-South lines just mentioned? As a matter of fact there is, besides the outline of the Alnsjö area, a particular feature indicating that a fault-like movement may once, before the chilling of the nordmarkite, have taken place at the eastern boundary of the Alnsjö lava field: viz., the occurrence of fragments of rhomb-porphyry lava and Cambro-Silurian (hornfels and crystalline limestone) at the top of Röverkollen Mountains (RK), just east of the Alnsjö area. These fragments occur as much as 150 m. *higher* than the much younger lavas just to the west. As we must assume that these fragments dropped down from the roof of the magmatic chamber, it follows that a dislocation of the bed rock, with subsidence to the west, must have taken place. There is, as a matter of fact, in the lava rock close to the eastern boundary distinct evidence of a breaking up along lines running more or less North-South. There can scarcely be any doubt that there is a close relation between the North-South dislocation cutting the Alnsjö mass, a dislocation which must be regarded as a phase in the central sinking of the Grefsen-Nitedal district, and the fault south of the nordmarkite.

Not all the plutonic masses of the Oslo region show evidence of basin structure or downfaulting. Along the northwestern part of the syenite-granite complex between Oslo and Lake Mjøsen (Fig. 4), the Archean occurs at rather high levels, in places 600-700 m. above sea level, which is as high as the highest Archean ground west and east of this part of the Oslo region. One might question whether the ground nearest the plutonic contact here may not have been uplifted, due to an upward movement of the adjacent igneous body. As a matter of fact, if we look at the map "Gran," on the scale of 1:100,000 we observe how, in the extreme northeast of the Cambro-Silurian area of Hadeland, the sub-Cambrian plane of denudation, where it can be observed, shows an abnormally steep dip westwards, that is, *away* from the plutonic mass

(Fig. 5), which occurs immediately to the east.[9] A strip of Archean is here exposed between the latter and the Cambro-Silurian as can be seen in Fig. 4. It would not be very surprising if magmatic masses caused subsidence in one area while they brought about uplifts in another. This is a very important problem of general interest and it is believed that future investigations along the boundaries of the Oslo plutonics may contribute toward its solution.

For the granite (granitite) mass around Drammen (Dr. in Fig. 4), a marked doming, here in places with rather concordant contact, seems to be characteristic, as has been shown by Kjerulf and Brögger for certain parts of it. The distribution of rocks on the southern side of the southeastern lobe of this granite, with a strip of Archean stretching ridge-like southward into the central fjord area, indicates a broad uplift in relation to the districts to the south and southwest, an uplift with the crust broken into innumerable fragments, as described by Brögger.[10]

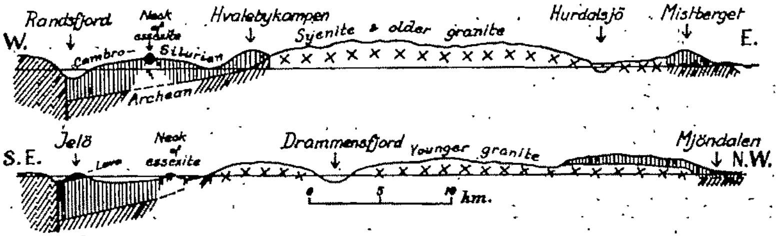


Fig. 5. Two somewhat simplified sections, one from the northern, the other from the more central part of the map area of Fig. 4, showing similar structural features.

If we continue the direction of the great Randsfjord fault (Fig. 4) towards the north-northeast, across the Archean territory, we pass into the main fault line along the Hunselv, and likewise, when following the Bundefjord line southwards, we soon join the imposing line of dislocation along the east side of the outer part of the Oslo fjord. This is one example of a certain regular arrangement in the structural features of the Oslo region, and there are many others. If we have two maps of the region and put one upside down, this character of correspondence at once strikes one. We may speak of a structural centre, situated in the central part of the large mass of granite at Drammen, the youngest plutonic mass of the region. The nordmarkite mass at Oslo, dealt with in some detail above, corresponds to the larvikite mass in the far southwest. A study of the map Fig. 4 will reveal a number of parallel structural features, and in Fig. 5 two rather similar sections are shown.

---

[9] Norges Geologiske Undersökelse, no. 97, 1923.

[10] Ueber die Bildungsgeschichte des Kristianiafjords. Nyt Magazin for Naturvidenskaberne, 30, 1886.

The fact that a number of regional tectonical features present themselves in several more or less parallel cases should be of great help in future efforts to trace the laws that are responsible for the upper Paleozoic crustal deformations in the Oslo region.

UNIVERSITY OF OSLO,
NORWAY.

maps of the region and put one upside down, this character of correspondence at once strikes one. We may speak of a structural centre, situated in the central part of the large mass of granite at Drammen, the youngest plutonic mass of the region. The nordmarkite mass at Oslo, dealt with in some detail above, corresponds to the larvikite mass in the far southwest. A study of the map Fig. 4 will reveal a number of parallel structural features, and in Fig. 5 two rather similar sections are shown.

The fact that a number of regional tectonical features present themselves in several more or less parallel cases should be of great help in future efforts to trace the laws that are responsible for the upper Paleozoic crustal deformations in the Oslo region.

University of Oslo,
Norway.

RHOMBOID RIPPLE MARK.

A. O. WOODFORD.

Bucher (p. 153, 1919) has proposed the term "*rhomboid (current-) ripple*" for "*small rhomboidal, scale-like tongues of sand*, arranged in a reticular pattern" produced experimentally by Engels (1905) as the first effect of transportation by a water current in gentle, uniform flow. But violent currents in water also impress rhomboidal patterns on sand, and hence, in this paper, the term *rhomboid ripple mark* will be used in a descriptive sense, to include all sharply rhomboid patterns developed on the surface of a mobile sediment. An example is given in Fig. 1. Braided rills which are not sharply and regularly rhomboid in pattern, are not included. Neither are the numerous V-shaped grooves which spread from the snouts of partly buried sand crabs (Hippidae, *Emerita analoga* in California), and which may in combination suggest an irregularly rhombic pattern.

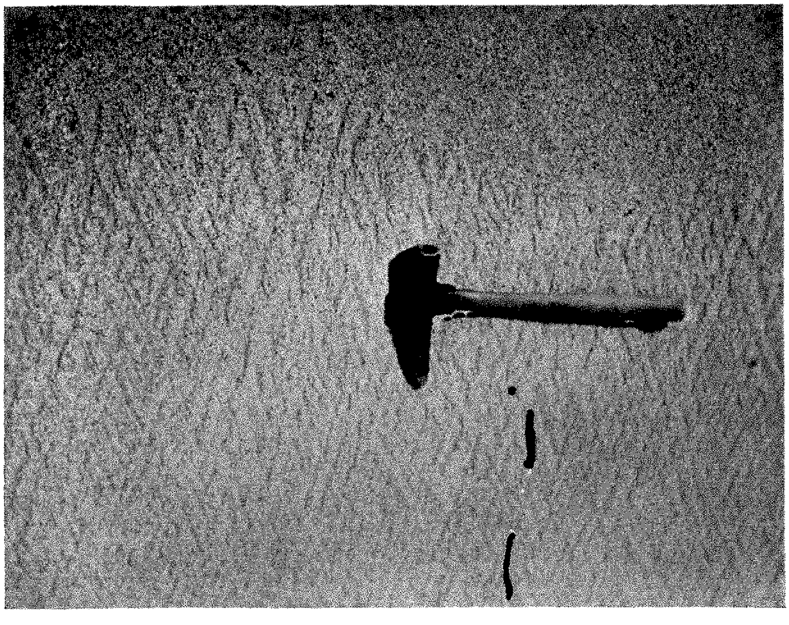


Fig. 1. Rhomboid ripple mark, Laguna Beach, Calif., March 29, 1933. The hammer gives the scale.

Several authors (Kindle: p. 34 and pl. 19b, 1917; Johnson: pp. 515-517, 1919; Kindle and Bucher: pp. 655, 656, 1932) describe and figure rhomboid ripple marks from modern beaches. In 1917 Kindle ascribed the imbricated pattern to, "The action of very small waves lapping and crossing each other from opposite sides of a miniature spit," but in 1932 Kindle and Bucher were inclined to explain the pattern in the light of the Engels' experiment mentioned above. Johnson calls the structures "backwash marks," and says (p. 517, 1919): "The thin sheet of water returning down the beach slope appeared to be split into diverging minor currents by every patch of more compact sand or particle of coarser material which impeded its progress, and the crossing of these minor currents resulted in the criss-cross pattern in the sand."

INTERFERENCE PATTERN UNDER RAPID FLOW.

The rhomboid pattern formed on sand looks very much like an interference effect. Therefore, before describing the observed pattern in detail, there will be presented some generalities concerning the waves which may form in water currents.

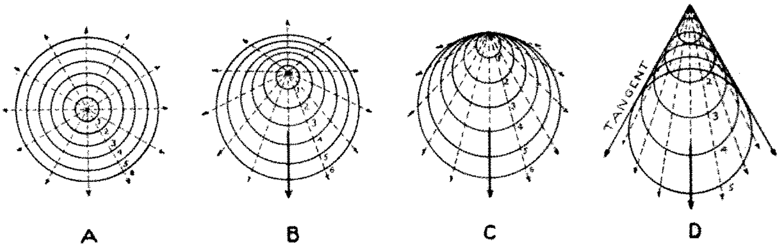


Fig. 2. Schematic sketches showing wave impulses spreading from a point, affected by various rates of flow. See text for explanation. After Rehbock.

First of all, the distinction must be made between *tranquil flow* and *rapid flow* (Rehbock: 1930; Bakhmeteff: 1932). In tranquil flow, the average velocity of the water is less than the wave velocity for the given depth; in rapid flow it is greater. The effect on waves is shown in Fig. 2, after Rehbock. If a pebble is tossed into quiet water, concentric waves are produced (A). If the water is in tranquil flow, the ripples are distorted (B). If a certain critical velocity is equaled or exceeded, the waves cannot be propagated upstream, but only down (C and D). In D there is suggested a cause for the rhomboid effect. A photograph (Fig. 3, from Rehbock p. 513, 1930) shows such rhombs on a water surface, repeated downstream by interference. The critical velocity between the tranquil and rapid states is given by the formula $V = \sqrt{g.h}$, where g is the acceleration of gravity and h is the depth of water. The shape of the rhombs varies with the depth and velocity, according to the formula $\sin \alpha = \frac{\sqrt{g.h}}{V}$ where α is the angle between the rhomb tangent (Fig. 2D), and the current direction.

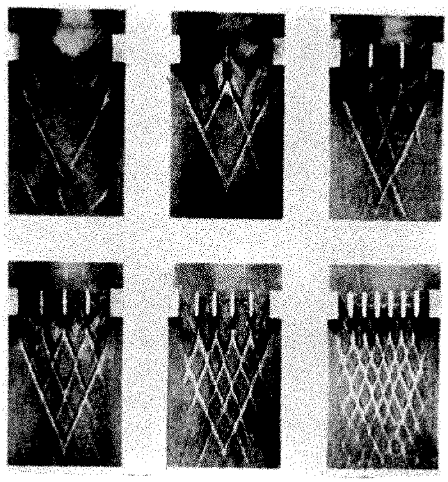


Fig. 3. Looking down on six model channels, which show the effects of abutments and slender piers in causing rhomboid ripples, when the flow changes from tranquil to rapid. From Rehbock.

It may be significant that in Engels' (1905) experiments mentioned above, a pier was placed at the head of the trough to promote the formation of rhombic tongues of sand. Perhaps the *slowly* tranquil flow was non-turbulent, and permitted the interference started behind the pier to be propagated downstream in simple regular fashion.

BEACH OBSERVATIONS.

Frequently during the past ten years, I have seen rhomboid ripple marks form on southern California sandy beaches, beneath the thinning waters of a retreating breaker, that is, in the "backwash" of the swash. As indicated by Johnson (p. 517, 1919) the rhomboid pattern is formed by a single current flowing down the beach, just as well as by a backwash which is the resultant of two or more oblique currents.

The rhomboid ripples are particularly well developed on the steep slopes cut into the broad curving beach at the mouth of Laguna Canyon, Laguna Beach, Orange County, California. I have found them there, forming or formed, on every one of the many occasions when I have searched for them. For example, on March 29, 1933, there was seen an extensive set, of which Fig. 1 shows a part, forming on a portion of the beach which had a seaward slope of $9^\circ\ 10' \pm 20'$. The sand was coarse, with grains up to 2 mm. in diameter, and not perfectly sorted. The rhombs were regular, but somewhat vague, smaller at the top than at the lower margin of the set, and averaging about two by one inches, with elongation parallel to the direction of slope. The rhomb pattern was impressed upon the sand during the final stages of the backwash, when the average velocity of the water was six and three-quarters feet per second (average of three trials over an 18-foot course; considerable acceleration down the beach). From these figures it was calculated that the rhombic ripples began to form at a velocity of 3.5 or four feet per second. The faintly etched rhomb pattern was immediately intensified through erosion by the thin film of water which flowed out of the sand and down the beach in the wake of the backwash. The rhombs in the sand began to form when the thinning, accelerating tail of the backwash was reduced to one or two inches in thickness, and simultaneously with the appearance of the corresponding rhombic (interference) pattern on the surface of the water. For a depth of one inch, $V = \sqrt{g.h} = 20$ inches per second; for two inches depth, $V = 28$ inches per second. After adding 20 per cent to these figures, because the formula gives somewhat low results for such shallow depths (Bakhmeteff, p. 258, 1932), even the second figure is slightly below the observed velocity at the upper edge of the rhomboid belt. Probably when the critical velocity was first passed, the centers of disturbance were too numerous and too irregularly spaced to produce an apparent, regular rhombic pattern.

Near low tide, on the afternoon of November 5, 1934, the dry coarse sand at the top of the active beach showed rather incomplete, but well-aligned rhomboid ripple marks. The rhombs were three to four and one-half inches long, one and a quarter to one and a half inches wide, with acute angles of 40° ± 3°, as shown in Fig. 4. By the formula $\sin \alpha = \frac{\sqrt{g.h}}{V}$, and assuming a depth of two inches, a current velocity of 8+ feet per second is indicated. If the depth was only one-half inch, a velocity of 4+ feet per second is indicated. The rhombic outline is formed by grooves 0.1 to 0.3 inches wide and 0.1± inches deep, which extend through the surface layer of coarse grit to a thin (0.1 inch) layer of finer sand below. Mechanical analyses of the two sand layers, made with round-hole sieves, are as follows:

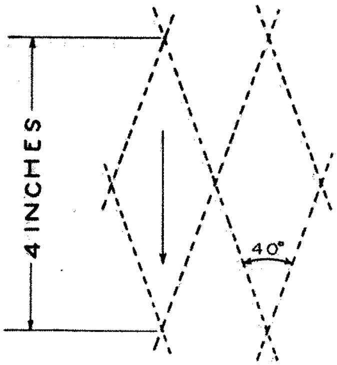


Fig. 4. Diagram of typical rhombs, Laguna Beach, Calif., November 5, 1934. Arrow shows current direction.

	Coarse surface layer (0.1″ thick)	Finer, second layer (0.1″ thick)
2–4 mm.	0.5%	0.0%
1–2 mm.	44.7	0.5
½–1 mm.	52.1	13.6
¼–½ mm.	2.7	85.9, mostly > ¼ mm.
⅛–¼ mm.	0.0	
Total	100.0%	100.0%

The belt of rhombs preserved at the top of the beach was only three or four feet wide, and no appreciable change of rhomb size or shape was noted in this short space. The average of three determinations of slope in this belt was 5° 15′ ± 5′.

On the flatter, 4° slopes down the beach the backwash was not forming rhomboid ripples, but instead branching rills localized by seaweed, or sand crab V's, Fig. 5. The pseudo-bird-tracks of Fig. 5 are made down slope from the points where sand crabs, *Emerita analoga* (Stimson), stick partially out of the sand beneath the water. Both the Hippidae V's and the braided rills are started at low velocities, as the backwash begins.

Twenhofel (p. 671, 1932) reports that "rill marks" which seem to be the structures here called rhomboid ripples, "Have been seen on many miles of beaches about the Mingan Islands, the Atlantic Coast about Cape Henry, and on beaches of California south of San Francisco and they probably are present on most sand beaches."

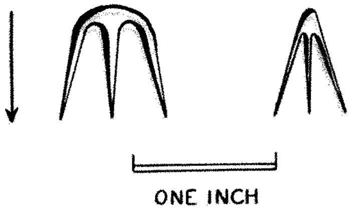


Fig. 5. Diagram showing types of grooves formed downslope from partially buried sand crabs. Arrow shows current direction.

EARTHQUAKE CRATER OCCURRENCE.

There has come to my attention only one natural occurrence of rhomboid ripple marks which was not located on a beach. This single example was found by Paul H. Dudley, marking the slopes of a little mud crater which developed during the Long Beach earthquake of March 10, 1933. The crater is shown in Fig. 6.

ORIGIN AND SIGNIFICANCE OF RHOMBOID RIPPLE MARKS.

It seems certain that the regularly rhomboid pattern in the sand is primarily the result of wave interference in the water, but the regularity of the patterns is surprising, and the exact manner in which the sand pattern is formed remains obscure. If depth were constant, the rhomb angles would indicate the current velocities, but as depth constantly decreases, at unknown and probably variable rates, it seems impossible thus to use the rhomb angles. Observation indicates that the rhombs are always elongated in the current direction.

RARITY OF FOSSIL RHOMBOID RIPPLE MARKS.

I have found no reference in the available literature to the occurrence of unmistakably rhomboid ripples in sedimentary rocks. Probably these structures are rarely preserved. They are only known to form in precarious places, where the chances of protective covering and preservation are slight. However, they probably will be found in the rocks, especially if looked for.

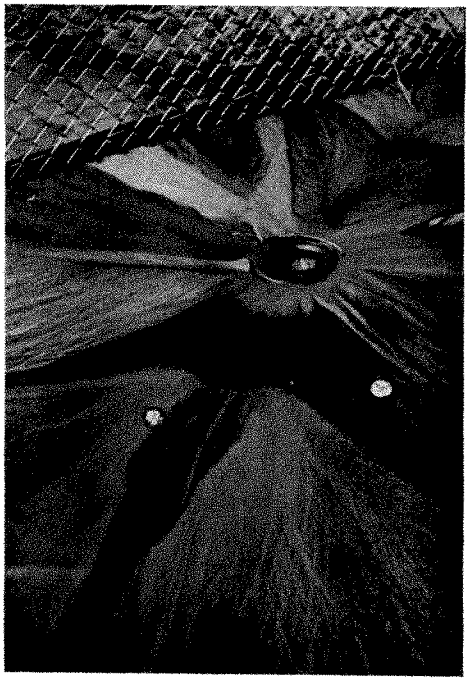


Fig. 6. Mud crater with rhomboid ripple marks, formed during the Long Beach earthquake of March 10, 1933. Vertical wire fence in background. The watch gives the scale. Photo by Paul H. Dudley.

SUMMARY AND CONCLUSIONS.

In *rapid flow*, waves are propagated down current only, and produce rhombic interference patterns. If the current is very shallow, rapid flow may be attained at a velocity so low that the rhombic pattern may be impressed as *rhomboid ripple marks* upon a mobile, sandy or even muddy bed.

Rhomboid ripple marks indicate relatively steep slopes, perhaps 5° or 10° or 15°. The current direction bisects the acute angles of the rhombs. If a single pattern changes in rhomb size and shape, the larger and more acute rhombs are to be found down the slope.

Rhomboid ripple marks are chiefly, but not exclusively intertidal features.

ACKNOWLEDGMENT.

I am indebted to my colleague, Professor Edward Taylor, for assistance in dealing with the hydraulic problem here considered.

REFERENCES.

Bakhmeteff, Boris A.: Hydraulics of Open Channels. 329 pp. New York, 1932.

Bucher, Walter H.: On Ripples and Related Sedimentary Surface Forms and Their Paleogeographic Interpretation. This Journal, vol. **197,** pp. 149-210, 241-269, 1919.

Engels, H.: Untersuchungen über die Bettausbildung gerader oder schwach gekrümmter Flussstrecken mit beweglicher Sohle. Zeitschr. f. Bauwesen, Bd. 55, S. 663-680. Mit Blätter 63 bis 67 im Atlas, & Textabb. 1 & 2, 1905. Especially in the present connection, pp. 675-677 and plates 65-66.

Johnson, Douglas W.: Shore Processes and Shoreline Development. 584 pp. New York, 1919.

Kindle, E. M.: Recent and Fossil Ripple-Mark. Canada Geol. Surv. Mus. Bull. *25,* 121 pp., including 33 pls., 1917.

Kindle, E. M., and Bucher, W. H.: Ripple Mark and Its Interpretation. In W. H. Twenhofel, Treatise on Sedimentation, 2nd ed., pp. 632-668, 1932.

Rehbock, Th.: Bettbildung, Abfluss und Geschiebebewegung bei Wasserläufen. Zeitschr. d. deutsch. geol. Ges., Bd. 81 (1929), S. 497-534, 1930.

Twenhofel, W. H.: Treatise on Sedimentation, 2nd ed. 926 pp. Baltimore, 1932.

Pomona College,
Claremont, Calif.

SEMIONOTUS CF. *GIGAS*, FROM THE TRIASSIC OF ZION PARK, UTAH.

CURTIS J. HESSE.

[Contribution from the Museum of Paleontology, at the University of California.]

The remains of Triassic fishes are not common in the western United States. The many specimens collected in the Connecticut Valley, and the rich faunas of Spitzbergen find no counterpart in the Triassic sections of western North America. The few forms from the marine sections of California, Nevada, and Idaho, are confined to the Elasmobranchii, and consist, chiefly, of detached teeth, fin spines and scales. The most complete fauna known in this region is that of the Lower Triassic shales (Spray River formation) near Banff, Alberta, Canada. From this locality five species have been collected, all of which are ganoids, with marked Paleozoic affinities.

The fresh water Triassic beds, which are also quite extensive, have offered but little in the way of fossil fish remains. The genus *Ceratodus* has been recorded from the Dockum beds of Texas by Case (1921, pp. 1-3, one fig.) and by Warthin (1928, p. 15, Fig. 1) on the evidence of two isolated teeth. Warthin also describes (op. cit., p. 17, Fig. 2) a quadrate with a fragment of the pterygoid attached as *Macropoma sp.* The fragment described under the name *Xenognathus obscurus* (Case, 1928, p. 6, Figs. 6-8) is of uncertain position, but is regarded by Case as a piscine in its affinities. In the Kanab Canyon region of southern Utah (from the Shinarump group of Powell), the genera *Pholidophorus* and *Lepidotus* were identified by Eastman (1917, p. 283, pl. 12, Fig. 4, pl. 13, Fig. 3) on fragmentary material. The specimen forming the basis of this report is, then, the most complete that has yet been described from the fresh water Triassic sections of western United States.

This fossil fish (U. C. Mus. Pal. no. 29530) was taken from a red shale, underlying a heavy sandstone member of the Chinle formation, in Zion National Park, Washington County, southern Utah. In this region the Chinle beds are of Upper Triassic age (Camp, 1930, p. 5), and while the known fauna of the Lower Chinle is close to that of the Lower

Newark of Pennsylvania, there is little in common between the faunas of the upper part of either section. The specimen was collected by Mr. R. A. Brown, about 100 yards northwest of Pine Creek bridge (U. C. Loc. no. V3024), while building a road from the main Zion Canyon up to Zion Tunnel. The slab was rescued from the débris of shale after firing a blast, which accounts for its incompleteness. The head, the caudal region as far forward as the anal fin, and most of the bone itself was destroyed, but the impression of the mid-region of the body is very clear and sharp. A few of the bony scales, fin rays, and fulcra are preserved. The specimen is of more value than it first seems, since the characters described in the following paragraphs are all clearly shown.

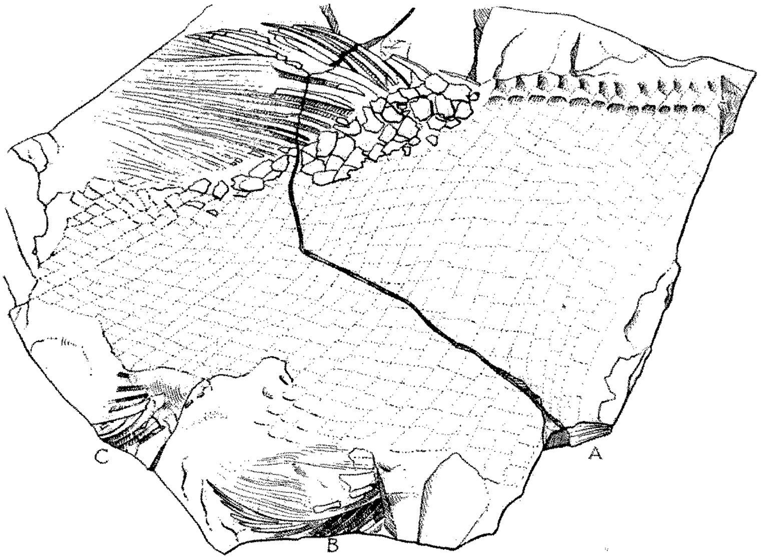


Fig. 1. *Semionotus* cf. *gigas*, from the Upper Triassic of Zion Park, Utah. About ½ nat. size. A. Pectoral fin. B. Ventral fin. C. Anal fin.

DESCRIPTION OF *Semionotus* CF. *gigas* FROM ZION PARK.

Of the ten or eleven known species of the genus *Semionotus*, all are small, seldom over twelve inches in length. However, in J. S. Newberry's monograph of the Triassic fauna and flora of the Connecticut valley, he described (1888, p. 49, pl. 14, Fig. 3) two exceptionally large specimens of this genus.

These were collected in the Boonton, New Jersey, Quarry, from which many other species of the same genus were taken. Unfortunately, the specimens of this large form, *S. gigas*, were not complete, and many of the characters were absent or obscure. It was a large fish measuring eighteen to twenty inches in length, with fin fulcra, rays, and scales of proportionate size. In its detailed characters it was not markedly different from the common species *S. agassizii*, a fact later pointed out by Eastman (1905, p. 83). In general, then, *S. gigas* is a typical semionotid, larger than the average species of that genus.

The Zion Park specimen is slightly smaller than the New Jersey form, to which I tentatively refer it. It was a robust fish approximately eighteen inches long, with smooth rhomboidal and oblong scales. There are thirty-one scale rows along the lateral line of the body, indicating within two or three rows the total body length. The transverse rows (counting from the base of the dorsal fin fulcra) number eighteen, and the depth of the body at this point is 123 mm., which is 31 mm. less than Newberry's estimate of the greatest body depth of *S. gigas*. The largest scales lie around the insertion of the pectoral fin, they are oblong (10 by 6 mm.) and cover the anterior ventral portion of the body. The scales of the dorsal and caudal regions decrease in size and become rhomboidal in shape. There is no evidence of striation or decoration of any kind, except on the most anterior dorsal scales, which may in a few cases have carried tiny studs. The row of spinous scales anterior to the dorsal fin, characteristic of the genus, is not well preserved. Judging from the impressions of these scales they seem to be about as well developed as those of *S. agassizii*, with spines a little heavier and less high. The dorsal outline resembles that of Newberry's figure of *S. agassizii* (op. cit., pl. 3). There are 17 dorsal fin fulcra, of which the largest is 42 mm. in length. These fulcra are heavy, broad based, and are all quite long. The dorsal fin rays number 11 or 12, the fin is large, its base including the fulcra is 85 mm. long, and its height (at the anterior margin) must have been somewhat greater than that figure. Only the most anterior part of the anal fin is preserved, the fulcra are heavy, and the impression of five fin rays is clear and sharp. The insertion of the anal fin is just anterior to the posterior border of the dorsal, while the ventral fin is inserted opposite the most anterior rays of the dorsal. The ventral fin is elongate and narrow, as preserved in this specimen, with thirteen fin fulcra and six or seven rays. The extreme posterior tip of the pectoral fin shows at the edge of the slab, six scale rows ahead of the base of the ventral.

Little more may be said of the specimen, since it is chiefly the impression of the body. Of the above characters all are readily seen, in spite of the fact that most of the actual bone is missing. In outline and most of its structural details it is similar to Newberry's figure (loc. cit., pl. 111) of *S. agassizii*, from which it varies only in size. Newberry describes this form (op. cit., p. 30) as from 10 to 12 inches in length, larger than any of the other eastern species except *S. gigas*. The latter species, as stated above, was supposed to be approximately 18 to 20 inches long, two to three inches longer than the Zion Park form. Size alone then, forms the basis of separation of the species *S. agassizii* and *S. gigas* (Eastman, 1905, p. 83), and on similar grounds I refer the Zion Park form to the latter species.

DISTRIBUTION OF THE GENUS *Semionotus*.

Species of this genus have not, thus far, been recorded outside the Newark series of the Connecticut Valley, New Jersey, and Virginia. From the Upper Triassic rocks of that area at least fourteen species are known. In Europe the earliest appearance of members of this genus is in the Bunter sandstone (Lower Triassic) of central Europe, from which two species, *S. alsaticus* and *S. gibbus* are recorded. From the Middle Triassic rocks of the old world only a single species, *S. altolepis*, has been described. By Upper Triassic time the genus was an important one, becoming world wide in its distribution and branching into a number of species. The Newark fauna of Eastern United States is of this age and from the Keuper and Rhaetic of Europe several species are known. From South Africa, in the Upper Karoo formation (Stormberg beds) the form *S. capensis* has been taken, and in the Lower Hawksbury-Wianamatta series of Gosford, New South Wales, Australia, the genus is known from two species, *S. tenuis* and *S. australis*. The specimen described in this report, from the Chinle Upper Triassic, indicates that the genus was also fairly widespread on this continent.

RELATION TO OTHER OCCURRENCES OF TRIASSIC FISHES IN NORTH AMERICA.

The family Semionotidae is an important one in the Mesozoic of the world, since it ranges from Upper Carboniferous or Permian to the Upper Cretaceous. In the Mesozoic rocks of North America only three other genera of this family (exclusive of *Semionotus*) are known, and each of these records may be open to some question. The most closely related of these other forms is *Lepidotus wolcotti* Eastman (1917, pp. 283-284, pl. 12, Fig. 4, pl. 13, Fig. 3), which is the first record of the occurrence of that genus in the United States. This species is based upon a fragmentary specimen, lacking both the head and the tail, and as stated by the original author, is imperfectly definable (op. cit., p. 283). In most of its characters *Lepidotus wolcotti* seems identical with the Zion Park *S. gigas*. From the figures given of the type, the two forms vary slightly in number of scale rows, fin rays, size, and possibly the acuminate scales of the dorsal ridge are more pronounced in the Zion Park specimen. Since figures are often misleading, and both specimens are at best fragmentary, it seems unwise to reassign either of the species at present. A second species questionably referred to the genus *Lepidotus* was collected in the Lakota sandstone of lower Cretaceous age, in South Dakota. This species, *L? lacotanus* Gregory (1924, p. 1-8, Figs. 1-2), seems to rest on more secure evidence, although questioned by the original author. As Gregory states (op. cit., p. 3) the specimen may be readily distinguished from *Semionotus* on the more advanced characters of body form and fins. However, members of that genus are not known above the Stormberg series of South Africa; so it seems possible that this form may represent an advanced member of that genus. Nevertheless, it resembles the known species of the genus *Lepidotus* more closely than it does any other form. Only a more complete specimen will definitely settle the reference of this species.

The second genus of the family Semionotidae recorded in North America, is that of *Tetragonolepis sp.?*, from the Triassic coal fields of Virginia. This was reported by Sir Phillip Edgerton, and was based upon a fragment of the mid-region of a large fish. Newberry (1888, p. 20) regarded this specimen as of uncertain position, and so it has since remained.

In the metamorphosed sandstones of Chicopee Falls, Massachusetts, a group of specimens was collected by J. H. Redfield, who later presented them to Yale. Newberry (op. cit., p. 70) described these specimens, referring them to the genus *Acentrophorus* Traquair. This species, *A. chicopensis*, was but provisionally referred here, since it seemed to resemble that genus very closely. Eastman (1904, p. 95), did not regard this reference as certain, but believed it to be the most accurate possible with the material.

From the foregoing account we may see that the family Semionotidae is best represented in North America by members of the genus *Semionotus*. Records of the other members of the family are uncertain, and all but one are confined to the Triassic.

LITERATURE CITED.

Camp, C. L.: A study of the Phytosaurs with description of new material from Western North America. Mem. Univ. Calif., vol. 10, pp. 1-161, 49 figs., 6 pls. 1930.

Case, E. C.: A new species of *Ceratodus* from the Upper Triassic of Western Texas. Occ. Papers Mus. Zoöl. Univ. Mich., no. 101, pp. 1-2, one fig. 1921.

————: Indications of a Cotylosaur and of a new form of fish from the Triassic beds of Texas with remarks on the Shinarump Conglomerate. Contr. Mus. Paleo. Univ. Mich., vol. 111, no. 1, pp. 1-14, one pl. 1928.

Gregory, W. K.: A fossil Ganoid fish (*Lepidotus* (?) *lacotanus*, new species) from the lower Cretaceous of South Dakota. Amer. Mus. Novit., no. 134, pp. 1-8, 2 figs. 1924.

Eastman, C. R.: A brief general account of fossil fishes: The Triassic fishes of New Jersey. Geol. Surv. New Jersey Ann. Rept., pp. 29-102, 14 pls. Report for 1904, issued in 1905.

————: Fossil fishes in the collection of the United States National Museum. Proc. U. S. Nat. Mus., 52, no. 2177, pp. 235-304, 23 pls. 1917.

Newberry, J. S.: Fossil fishes and fossil plants of the Triassic rocks of New Jersey and Connecticut Valley. Monogr. U. S. Geol. Surv., no. 14, pp. 1-74, 17 pls. 1888.

Warthin, A. S.: Fossil fishes from the Triassic of Texas. Contr. Mus. Paleo. Univ. Mich., vol. 111, no. 2, pp. 15-18, one pl. 1928.

University of California,
Berkeley, California.

SCIENTIFIC INTELLIGENCE.

Chemistry.

Crystals and the Polarising Microscope. A Handbook for Chemists and Others; by N. H. Hartshorne and A. Stuart. Pp. vi, 272; 217 figs. London, 1934 (Edward Arnold & Co.), New York (Longmans, Green & Co., $6.00).—This well-written and well-illustrated manual should be in the hands of every chemist. The relatively simple method of examining crystalline materials which is afforded by the polarising microscope has long been indispensable to the petrologist and crystallographer but the many and varied chemical applications of the method have not received the attention they deserve. The authors give a good concise outline of the principles of crystallography and crystal structure and an excellent presentation of the theoretical and practical aspects of optical properties of crystals and their measurement. A chapter on the use of the method in chemical practice with numerous specific examples and references gives the chemist a good picture of the possibilities of the method. A final chapter of experiments should serve as an elementary course for the beginner. It is unfortunate that such an excellent book could not be sold at a lower price which would insure its place in the working library of every chemist and physicist. J. F. SCHAIRER.

The Carbohydrates; by E. F. Armstrong and K. F. Armstrong. Pp. vii, 252. New York, 1934 (Longmans, Green and Company, price $6.50).—The latest edition of this well known reference book has been brought quite up-to-date, even to the inclusion of a section on ascorbic acid (Vitamin C). In fact, it is scarcely fair to call this a new edition, for it has been completely rewritten. This is in part due to the fact that since the last edition of "The Simple Carbohydrates and the Glucosides," published in 1924, the work has been divided into the present volume "The Carbohydrates," and a previous volume, "The Glycosides," published in 1931.

The book is extremely valuable, especially to students and teachers who wish to get the fundamentals of carbohydrate chemistry in an easily readable and understandable form. In the words of the authors, "It is primarily our object to appeal to those interested in sugar chemistry from the biochemical aspect, and we have therefore confined our attentions to the natural sugars and their derivatives and restricted as much as possible the discussion of intricate structural problems."

In this aim the authors have been remarkably successful. The structure of glucose is first considered, followed by the proof of the configuration of the hexoses. This leads to a discussion of the ring structure of the sugars, muta-rotation, and the relation of configuration to optical activity. Then comes the more detailed discussion of the individual monosaccharides, oligosaccharides, and polysaccharides. Finally, there are several special chapters, of which one on Configuration and Biological Behavior is exceedingly thought provoking.

It is particularly timely that this work should have come out now, after years of dispute and uncertainty in regard to sugar structures and the methods for their determination—years which have left the "lay" chemist in a very confused state. Now, however, due largely to the monumental works of Haworth and many others, a reasonable degree of certainty and order has finally prevailed, and the authors' readers will all be indebted to them for having portrayed the present state of carbohydrate chemistry in so excellent a fashion. R. D. COGHILL.

Electrolytes; by HANS FALKENHAGEN. Translated from the German by R. P. BELL. Pp. 348; 105 figs. Oxford, 1934 (Clarendon Press, price $9.50).—This translation of Falkenhagen's treatise on electrolytes is a valuable contribution to the English physico-chemical literature and should serve both as a guide to future research and as a means of stimulating interest in the important field of electrolytic solutions in the English-speaking countries. It is the first book in English which contains the general treatment of the modern theory of equilibria and irreversible processes in electrolytic solutions and since the author has made valuable contributions to this theory it is particularly valuable and authoritative.

The English edition contains all the material of the German edition to which have been added discussions of recent developments, the most important of these is an appendix by Professor R. H. Fowler upon the quantum mechanics of electrode processes.

The first six chapters (100 pages) are devoted to a discussion of the properties of electrolytic solutions. The development of the modern theory begins with Chapter VII where the fundamental ideas of Milner and Debye are stated and the ionic atmosphere is defined. This is followed by two important sections, the first has to do with the statics of ionic atmospheres and thermodynamic properties and the second with the dynamics of ionic atmospheres and irreversible processes. These two long chapters are the most important in the book. The second of them is particularly valuable since in this field the author is a leading authority. The treatment of electrolytic conductance and frequency effects upon electrolytic conductance is admirably carried out.

The presentation of the theory of viscosity given in Chapter X is in the writer's opinion too short to be satisfactory. Since the development of the theory of viscosity of electrolytic solutions is Professor Falkenhagen's work, a more detailed account than the one given would be a valuable addition in the general literature of the subject.

A chapter upon the theory of concentrated solutions is always difficult. The theories are inexact and complicated and the experimental material of high accuracy is quite voluminous. Taking it all in all, the discussion of the theories of concentrated solutions and their criticism is well done and the author's point of view well taken. As a whole, the book is an excellent contribution as an exposition of the theories of this subject. It is not, nor does it attempt to be, a really adequate presentation of the physical chemistry of electrolytic solutions.

The omission of the excellent index in the German edition and the substitution of a completely inadequate one-page index in the English text is in the writer's opinion a serious mistake. Indeed, it is inconceivable why such a sacrifice was made. H. S. HARNED.

PHYSICS.

From Galileo to Cosmic Rays; by HARVEY BRACE LEMON. Pp. 450; 100 plates, many figs. and portrait as frontispiece. Chicago, 1934 (University of Chicago Press, $5.00; Education Edition, $3.75; Stereoscope 75 cents extra. Trade Edition with Stereoscope, $5.00).—Arising out of the need for a shorter and less technical book to assist entering students at the University of Chicago in their general science examination, this book is in several respects unique. Not a few surveys of science have been published in recent years, intended for text-book or popular use, but the present volume is the first to attempt this for physics for college grade in a whole-hearted manner. The pedagogy exhibited is progressive and carefully considered. The style is direct and personal so that one is always in an unusual degree aware of contact with the author. While different techniques are used in developing various aspects of the subject, one consistently used throughout is the employment of simple drawings and sketches on the one hand, to replace the usual technical and too often formidable diagrams, and of photographic reproductions of actual experiments with simple apparatus on the other. Many of the latter have the novelty of having been taken stereoscopically, and stereoscopic lenses may be obtained with the edition for the purpose of viewing these three dimensional pictures more readily. The subject matter is ably and accurately presented; the outline of topics follows quite closely that of the ordinary text. Emphasis is of course laid upon inference and deduction from experiments rather than upon more mathematical reasoning and formulation. The frequent drawings by Chichi Lasley lend a whimsical and often a comic touch. There will undoubtedly be teachers who will frown upon sketches like that of electron gnomes fleeing in panic from a hot body or of a burly trainer attempting to weigh an electron on gymnasium scales, but it is doubtful whether the reading student will disapprove. A more serious matter to consider is whether the author may antagonize his readers (especially college students) by giving the impression of "talking down" to them, an impression which may be more readily dispelled in a lecture than in a book. A. T. W.

GEOLOGY.

Kyanite and Vermiculite Deposits of Georgia; by LOUIS M. PRINDLE (with contributions by W. D. JOHNSTON, JR., GEOFFREY W. CRICKMAY, B. W. GANDRUD and RICHARD W. SMITH). Geological Survey of Georgia, Bulletin No. 46. Pp. ix, 50; 4 text figs.; XI pls. Atlanta, 1935 (Stein Printing Company).—Since 1917, workable deposits of kyanite, sillimanite, and andalusite have been sought for because of their value in the manufacture of refractory porcelain articles. Hence this report in which the properties of these minerals and their industrial uses are outlined. Occurrences of kyanite in Georgia are described in some detail. The deposits, occurring in the Piedmont area, are of two types: micaceous kyanite-staurolite-garnet schists and kyanite-quartz veins. Each may give rise to residual and placer accumulations. The relatively low-grade kyanite schists of Habersham and Rabun Counties are considered the most promising source of the mineral. They outcrop in a U-shaped belt 30 miles long and up to 1000 feet wide. Table and flotation tests have produced clean concentrates from micaceous kyanite-garnet schist containing 4 per cent kyanite. Residual and placer concentrations are at present being worked on a small scale.

The vermiculite deposits of Georgia have been examined in part, as the bronze color, lightness, and heat insulating and acoustical properties of this mineral render it valuable. Commercial quantities may occur in Towns County, possibly forming a continuation of the North Carolina vermiculite zone. The deposits are in hydrothermally altered basic igneous rock. HENRY HOTCHKISS.

The Navy-Princeton Gravity Expedition to the West Indies in 1932. Pp. 54; 16 text figs., 2 half-tone plates, index map, 1 large folded chart. U. S. Hydrographic Office, Washington, 1933.—The expedition that furnished the data for this report was initiated by the Department of Geology of Princeton University. As the chief object was determination of gravity values, a submarine and tender furnished by the U. S. Navy were essential items of equipment. Equally important was the help of Dr. F. A. Venig Meinesz of the Netherlands Geodetic Commission, who brought with him and operated the multiple pendulum apparatus with which he has determined gravity from a submarine in many parts of the world.

A narrative of the six-weeks' cruise is given by T. T. Brown, of the Naval Research Laboratory. Computations of the gravity observations are presented by E. B. Collins, of the U. S. Hydrographic Office. The longest chapter of the report gives a discussion of the observations from the geological point of view, by H. H. Hess. Several remarkable facts emerge from study of all gravity values in the West Indian region, with the aid of profiles based on sonic soundings. The deep Bartlett Trough is strongly positive, and in general the positive anomalies vary directly with the depth of water. A similar relationship is indicated, but with fewer stations as a basis, in the Gulf of Mexico and in the Caribbean Sea. On the other hand there is a belt of negative anomalies extending along the north side of Cuba and becoming especially pronounced north of Haiti and Porto Rico. This persistent belt, similar to the strip of negative anomalies found by Meinesz bordering the East Indian islands, may have an important relation to existing tectonic forces. This view is supported by the grouping of seismic centers in Porto Rico and Haiti and along the Bartlett Trough. Hess suggests that the Trough may lie along a shear zone that accommodates differential horizontal movement between regional blocks on the north and south.

The kind of investigation carried out by the expedition has great promise. Geologists and geophysicists will await with much interest further extension of the gravity network, especially to the southeast, in the vicinity of the Lesser Antilles.

C. R. LONGWELL.

Géologie Appliquée; by E. RAGUIN. Pp. 392, 110 figs. Paris, 1934. Masson et Cie., Bd. Saint Germain 120; 38 francs, paper binding.—Four chapters of this work, comprising the first 162 pages, are devoted to the essential principles of geology. In this short exposition emphasis is placed on the various kinds of rocks, their mode of occurrence, their origin, and their structure. One chapter explains the principles of stratigraphy, including the use of fossils in correlation.

The remaining nine chapters are taken up with practical applications of geology in mining, construction of tunnels and dams, obtaining water supplies, and drilling for oil and gas. Many specific examples increase the interest of the discussion and at the same time add to its value. The final chapter explains several methods of geophysical prospecting—gravimetric, magnetic, electrical, and seismic—and cites practical results that have been obtained by each method.

The book succeeds very well in demonstrating the many useful aspects of geology. It seems to the reviewer, however, that parts of the treatment of principles in the first chapters are too brief and general to be of real value. For example, the few pages devoted to fossils, illustrated by excellent half-tone figures, are doubtless interesting to a lay reader; but they are wholly inadequate as equipment for a student or an engineer who wishes to make practical use of fossils. There is serious question whether in preparing a book of this kind the author ought not assume a knowledge of elementary principles and devote all available space to explaining the practical applications of these principles. C. R. LONGWELL.

Bibliographic Index of Paleozoic Ostracoda; by R. S. BASSLER and BETTY KELLETT. Geol. Soc. America, Special Papers, No. 1, pp. xiii + 500, 24 text figs., 1934.—This good-looking and well-printed index, which inaugurates the series of Special Papers made possible by the Penrose bequest to the Geological Society of America, presents the entire bibliography and synonymy of the world's known Ostracoda, numbering about 2380 species and varieties grouped in 164 genera or subgenera and 17 families. The book is, however, more than a bibliographic index, since it describes and illustrates the morphology of the ostracods (pp. 1-7), methods of study (7-9), orientation of the valves (9-11), and criteria of classification (11-13). This matter is followed by the classification adopted by the authors, with diagnoses and illustrations of the families and subfamilies and the genera and subgenera (13-47). Next come faunal lists for the many formations in which the ostracods occur (48-97), and the formations arranged in six correlation tables. The list of papers used in making the present index occupies pages 98-144, while the remainder of the book presents the entire bibliography and synonymy of the genera and species, with locality and horizon, and catalogue number of the types which are in the United States National Museum. C. S.

The Mesozoic Paleontology of British Somaliland [Part II of the Geology and Paleontology of British Somaliland]; by W. A. MACFAYDEN et als. Pp. 228; 25 pls. Govt. of Somaliland Protectorate (London), 1935. Price £1 10 s. net.—This volume by eight authors is devoted to the systematic paleontology of the Jurassic and Cretaceous strata of British Somaliland.

The foraminifera (28 species) are described by W. A. Macfayden; the corals and hydroids (12 species) by H. Dighton Thomas; the Jurassic echinoids (23 species) by Ethel D. Currie; the Cretaceous echinoids (9 species) by H. L. Hawkins; the crinoidea (8 species) by F. A. Bather; the brachiopods (54 species) by H. M. Muir-Wood; the pelecypods and gastropods (61 species) by L. R. Cox, and the cephalopods by L. F. Spath.

Old species are annotated but not described, and many of the described species, based on fragmentary remains, are not named. The section by Miss Muir-Wood includes 8 new genera of brachiopods besides many new species. C. O. DUNBAR.

MISCELLANEOUS SCIENTIFIC INTELLIGENCE.

Subsidence within the Atmosphere; by JEROME NAMIAS. Pp. 61. Harvard Meteorological Studies, No. 2. Harvard University Press, 1934 (price $0.85).—The first part of this paper discusses, with diagrams, the theory of atmospheric subsidence. The second section gives the salient features in connection with three meteorological situations, with special emphasis on the accompanying subsidence inversions. The maps show fronts, air masses, isobars, precipitation areas, and positions of aerological stations.

Subsidence is a stabilizing process which takes place primarily at the upper levels in the atmosphere. Within a polar air mass a sharp subsidence inversion often develops, generally associated with a marked drop in the humidity from the bottom to the top of the inversion, a feature that commonly distinguishes it from a frontal inversion. The temperature and moisture discontinuities at these inversions often are so pronounced as to indicate the presence of one or more contributing factors in addition to subsidence. Indeed, even the original development of these temperature inversions is not yet clearly understood.

The subsidence due to the outflow of air in anticyclones cannot account for the rapid development of subsidence inversions in many winter anticyclones. Subsidence masses are extensive domes which at times and places reach beyond the five kilometer level and, again, practically intersect the surface of the earth in their periphery. After a subsidence dome is once established, the air above its surface sinks and spreads. At the upper levels in the atmosphere the process is practically adiabatic and therefore the potential temperature of each subsiding particle of air remains very nearly constant. The tendency is to maintain a constant potential temperature at the base and at the top of the inversion.

U. S. WEATHER BUREAU, WASHINGTON, D. C. C. L. MITCHELL.

Publications of the Royal Astronomical Society.—A third edition of the Franklin-Adams Chart of the sky is proposed in case sufficient support is promised. Two hundred and six sheets are planned, each 15° x 20°. There would be three sections: (1) North Pole to Decl. 22°; (2) Decl. +22° to −22°; (3) Decl. −22° to South Pole. Price, with carriage, 27 pounds. Subscriptions will be accepted at the same rate for one or two sections. Apply to the Assistant Secretary, R. Astronomical Society, Burlington House, London, W. 1.

Scientific Survey of Porto Rico and the Virgin Islands, vol. 14, pt. 2, pp. 111-260, *Insects, Homoptera (excluding the Sternorhynchi)*; by HERBERT OSBORN. New York Academy of Sciences, 1935.

Of the one hundred and fifty species mentioned, forty, including those described as new, are known to occur only on the island of Porto Rico. All the species but nine are cicadellids and fulgorids. The text includes a brief ecological discussion, keys to families and sub-families and in some cases to genera and species, descriptions of species, and notes on host plants. Many of the species are illustrated. R. B. FRIEND.

Planetario Tascabile Hoepli; compiled by G. L. ANDRISSI and A. TOSI. Milan, 1935 (Hoepli Publishing Co., Lire 20).—Hoepli, the Italian editor who, with his hundreds of volumes ranging from "The Principles of Rabbit Breeding" to "How to Climb Mountains," has done more, since the turn of the century, to popularize science than any other one editor we can think of. He has now issued a very ingenious contraption called the "Pocket Planetarium," which will prove handy to both scholar and amateur in the field of star science and star observation.

It consists of fourteen circular blue cardboard diagrams of the star hemispheres, bound in book format, and carried in a container into which the round volume, once opened, is again inserted upright and rotated according to the instructions which accompany the publication. Thus, a reproduction of the night skies at any given hour and *at any given point of the planet* can be obtained.

This volume—a very neat job for the price—should be of interest to travelling amateur astronomers. It is fairly easy, even for someone unacquainted with Italian, to follow it. U. RANIERI.

Biology for Everyman; by J. ARTHUR THOMSON, edited by E. J. HOLMYARD. Two volumes. Pp. x, 1561; with 492 figs. New York, 1935 (E. P. Dutton and Co., price $5.00).—These two thick volumes bring together the most valuable of the vast accumulation of observations, and generalizations gathered during a long lifetime spent in an intimate study of the lives of animals and plants. No other English writer, since Darwin and Huxley, has acquired a broader knowledge of the science of life or an equal facility in presenting in simple language those facts about the living world which to the great mass of readers prove both interesting and educational.

No aspect of vital phenomena is omitted, for each group of organisms is discussed systematically and the story leads from the simple reactions of the most primitive types to the psychic life of man. How these many parts of the web of life fit together and how they may serve in the construction of a broad philosophy of life have been questions that have actuated the author for many years. To explain the answers most clearly to the unscientific reader has been one of his chief ambitions. These volumes, completed during the last hours of his life, are sufficient evidence that this ambition has been realized.

Used as a reference book, the reader will find in the elaborate index, covering 74 pages, a guide to the answer to almost any question in biology that he is likely to ask, as well as to thousands of others well worth asking. W. R. C.

A Manual of the Common Invertebrate Animals (*Exclusive of Insects*); by HENRY SHERRING PRATT. Thoroughly revised edition, pp. xviii, 854, with 974 figs. Philadelphia, 1935 (P. Blakiston's Son and Co., price $7.50).—During the past nineteen years "Pratt's Manual" has come into regular use in practically every zoological laboratory in the country and has become almost indispensable to every investigator interested in the systematic study of invertebrates. In the meantime the classification of the various groups has been materially changed and other specific and generic names have been substituted for many of those used in the first edition.

This revised edition not only brings the nomenclature up to date but includes many additional species. More than a score of specialists have participated in the revision of the separate groups. Analytical keys are given for every phylum, order, family and genus, thus facilitating the identification of the two thousand or more genera and species included. No group of the invertebrates except the insects is omitted, but those forms which are more common, more conspicuous or more important either as friends or foes of man are naturally given the greater prominence.

With this book in hand one can readily find not only the name but also the most essential facts about the life of almost any one of the animals, other than insects or vertebrates, which he is likely to find along the seashore, in streams or lakes, in fields or forests, or as parasites of other animals. In this respect the book has no competitor; it is unique in its field and will be welcomed by every systematic zoologist and by many amateurs. For the less experienced student the glossary of technical terms will be found useful. W. R. C.

OBITUARY.

MICHAEL IDVORSKY PUPIN.

The marvelous story of Pupin, who died on March 12 at the age of 76, is told in his autobiography, "From Immigrant to Inventor." A Serb, born in 1858, in Idvor, in what is now Czecho-Slovakia, he ran away from Prague high school when he was 16 and reached New York almost penniless. He heroically made his own way; received an A.B. from Columbia in 1883; aided by the first John Tyndall Scholarship he studied at Cambridge, England, and with Helmholtz and Kirchhoff at Berlin where he received his Ph.D. in 1889. Beginning as instructor in mathematical physics at Columbia, he was made professor of electromechanics in 1901 and became emeritus in 1929.

In contributing as a past-president (1925-26) of the American Institute of Electrical Engineers to its 50th anniversary (*Electrical Engineering*, May, 1934) he chose a field in which lay his own outstanding interest and achievement, "The Equation of Electrical Propagation," in which he indicated his own contributions, mathematical and practical, in the "Pupin" or loading coil which made possible the long distance telephone.

In 1915, on the evening following the initiation of the New York-San Francisco telephone service there was a dinner of the officers of the Electrical Institute. The eloquent toastmaster, Gano Dunn, former student of Pupin, described the historic achievement in glowing terms, and, with eulogy unstinted, presented Inventor Pupin as the scientist who made it possible. Doctor Pupin quietly told the story of how it came about. Mr. Carty, eminent telephone engineer (absent on account of his strenuous activities incident to the demonstration), came to him with a problem. Elaborate observations and tests had proved that it was the electrostatic capacity of the line that limited talking distance. What could be done? His scientific studies, Pupin said, enabled him to meet the problem with a mathematical and practical solution. He added, "When the engineer has formulated his problem, it is more than half solved." It was thrilling—the brilliant scientist, showered with congratulations and glory, generously sharing honors with the analytical engineer.

A patent for tuning circuits was sold by Pupin to the Marconi Company. In the X-ray field he made the first photograph in this country as a guide in surgery; he invented a method of rapid X-ray photography and discovered the secondary radiation.

He has held office in many scientific and engineering societies; he received over half a dozen medals and 18 honorary degrees.

Of Pupin's early papers (1890-1895) about half—the more scientific ones, basic to later achievement—appeared in seven issues of this Journal; they dealt with electrical discharges in a vacuum, electrical oscillations, resonance analysis and electromagnetic theory.

I made a memorable call on him a few years ago at his country place near Norfolk, Connecticut, and in the course of it he became eloquently indignant at those who decried the value of scientific and engineering achievement. He did not deal in petty controversy but chose his own ground, having in preparation at the time a magazine article and a book portraying "The Romance of the Machine."

He was an inspiring teacher; Millikan was one of his students. He was human and sympathetic, as attested by his services to the Serbians in post-war distress. Apropos of his address (*Electrical Engineering*, March, 1932), "The Power Age," on receiving the John Fritz Medal, "His words were full of the deepest philosophy of physical science and the loftiest appeal to the finest spirit in mankind. He characterized as essential to man's attainment of the good life an understanding of the moving power of heat, of the moving power of electricity and of the moving power of love, each of divine origin and eternal."

CHARLES F. SCOTT.

OBITUARIES.

Dr. Jay Loring Arnold, professor emeritus of electrical engineering at New York University, and well known physicist, died on April 23 at the age of sixty-seven.

Dr. Herbert B. Baker, professor emeritus of chemistry at the Imperial College of Science and a noted war gas expert, died on April 28 at the age of seventy-three.

Dr. Jesse Erwin Day, nationally known professor of chemistry at the Ohio State University, died on April 20 at the age of forty-seven.

Dr. David Griffiths, botanist in the Federal Bureau of Plant Industry, died on March 19 at the age of sixty-seven. He devoted his last twenty years to bulb production, devising practical methods of growing and handling the bulbs of narcissi, tulip, hyacinth, as well as Easter, Madonna, Henry, Speciosum and Tiger lilies.

Dr. Joseph Edward Guthrie, professor of zoology at the Iowa State College, died on April 16 at the age of sixty-three.

Dr. A. Hantzsch, formerly professor of chemistry in the University of Leipzig, died on March 14.

Professor R. O. Herzog, noted for the discovery of the microcrystalline structure of cellulose, died at Zurich on February 4 at the age of fifty-six.

Dr. William Richard Hodgkinson, professor of chemistry and metallurgy for thirty-one years at the Military College of Science, Woolwich, England, died on April 8 in his eighty-fourth year.

Dr. John Livingston Rutgers Morgan, since 1905 professor of physical chemistry at Columbia University, died on April 12 at the age of sixty-two.

Sir William Morris died on February 26 in North Wales at the age of eighty-seven years. He contributed much to geodesy and established, with Sir David Gill, a geodetic survey on Cape Colony and Natal.

Emanuele Paternó, a leading Italian chemist, died on January 18 at the age of eighty-seven years. He was director of the Chemical Institute of Rome and contributed much to science during his life. In addition to his research work, Paternó excelled as an organizer.

Dr. Robert Alexander Robertson, professor of botany at the University of St. Andrews for many years, died on January 15.

Dr. Herbert Weld, the English geographer and archaeologist, died on February 4 at the age of eighty-three.

PUBLICATIONS RECENTLY RECEIVED.

A Manual of the Common Invertebrate Animals Exclusive of Insects; by Henry Sherring Pratt. Revised Edition. Philadelphia, 1935 (P. Blakiston's Son & Co., $7.50).

Relativity Gravitation and World-Structure; by E. A. Milne. New York, 1935 (Oxford University Press, $8.00).

Laboratory Manual for General Geology (Physical and Historical); by Mark H. Secrist. New York, 1935 (The Macmillan Co., $1.75).

A Textbook of General Botany; by Gilbert M. Smith et al. Third Edition. New York, 1935 (The Macmillan Co., $3.50).

Pression Solaire et Atomes la Circulation de L'Energie par le D'Georges Froin. Paris, 1935 (Librairie Louis Arnette).

A Laboratory Manual of General Botany; by Emma L. Fisk and Ruth M. Addoms, Revised Edition. New York, 1935 (The Macmillan Co., $1.00).

Weeds; by Walter C. Muenscher. New York, 1935 (The Macmillan Co., $6.00).

A Textbook of Biochemistry: Edited by Benjamin Harrow and Carl P. Sherwin. Philadelphia and London, 1935 (W. B. Saunders Co., $6.00).

Geological Survey of Georgia. Abstract of Bulletin 46. Kyanite and Vermiculite Deposits of Georgia; by Louis M. Prindle and others. Richard W. Smith, State Geologist, 425 State Capitol, Atlanta, Georgia.

The Geology of the Orkneys; by G. V. Wilson et als. Memoirs of the Geological Survey of Scotland, Edinburgh, 1935 (5sh. 0d. net).

Annual Report of the Director of Mines and Government Geologist for 1933. Adelaide, South Australia, 1934.

Text-Book of Mycology; by Ernst Athearn Bessey. Philadelphia, 1935 (P. Blakiston's Son & Co., $4.00).

Preliminary Note on Alkaline Rhyolites from Tokati, Hokkaido; by Tadahiro Nemoto. (Journal of the Faculty of Science. Hokkaido Imperial University, Sappora.)

Principles of Genetics and Eugenics; by Nathan Fasten. Boston, 1935 (Ginn & Co., $2.80).

The Carnegie Foundation for the Advancement of Teaching. Annual Review of Legal Education in the United States and Canada for the Year 1934. Twenty-ninth Annual Report.

Report of the Librarian of Congress for the year ending June 30, 1934. Washington, D. C.

Minerals Yearbook for 1934. Washington: Government Printing Office, 1934.

Mineral Resources of the United States for 1931. Part I, Metals. Part II, Nonmetals. Washington: Government Printing Office, 1934.

Smithsonian Institution. Washington, 1935. Explorations and Field-Work of the Smithsonian Institution in 1934. Pp. 88; 84 figs.

Magnetism and Matter; by Edmund C. Stoner. London and New York, 1935 (Methuen & Co., E. P. Dutton & Co., $5.50).

State of Washington Division of Geology, Harold E. Culver, Supervisor. Reports of Investigations. No. 2. Oil and Gas Possibilities of Western Whatcom County; by Sheldon L. Glover.

U. S. Geological Survey. Bulletin 848. The Microscopic Determination of the Nonopaque Minerals. Second Edition; by Esper S. Larsen and Harry Berman. Bulletin 850. Quicksilver Deposits of Southwestern Oregon; by Francis G. Wells and Aaron C. Waters.

Western Australia Geological Survey. Bulletin 95. The Physiography (Geomorphology) of Western Australia; by J. T. Jutson. (Maps to accompany it.) Second Edition. Perth, 1934.

Science and the Human Temperament; by Erwin Schrödinger. Translated by James Murphy and W. H. Johnston. New York, 1935 (W. W. Norton & Co., $2.50).

INDEX TO VOLUME XXIX.*

A

Acoustics, Applied, Olsen and Massa, 76.
Agar, W., minerals, pegmatite, Falls Village, Conn., 56.
Allsop, C. B., Spectrophotometry, Absorption, 61.
Andrissi, G. L., Planetarium, 539.
Angola, geology, Mouta and O'Donnell, 64.
Animals, Caves, Wolf, 75.
—Common Invertebrate, Pratt, 540.
Apes, anthropoid, Hrdlicka, 34.
Applied Geology, Raguin, 536.
Aqueducts, Roman, Van Deman, 69.
Ardnamuchan, Richey, 466.
Arkose deposits, Mexico, Krynine, 353.
Armstrong, E. F., Carbohydrates, 532.
—**K. F.**, Carbohydrates, 532.
Astronomy, Jones, 310.
—and Astrophics, Bruggencate, Freundlich et al., 223.
Atmosphere, Subsidence within the, Namias, 538.
Atom, the Mystery of, Wilson, 62.
Atwater, G. I., galena dolomite, upper Mississippi Valley, 98.

B

Bassler, R. S., Ostracoda, Paleozoic, Index of, 537.
Berry, W. B., David White, obituary, 390.

BIOLOGY AND BIOLOGICAL WORKS.

- Animals, Caves, Wolf, 75.
- —Common Invertebrate, Pratt, 540.
- Biologist, Philosophy of a, Haldane, 468.
- —Research of, Rodolico, 468.
- —Everyman, Thomson, 539.
- Body, the Human, Martin, 471.
- Chimpanzee, Yerkes, 389.
- Evolution, Morgan, 468.
- Homoptera, Insects, Osborn, 538.
- Parasites, Protozoan, of Fishes, Kudo, 75.
- Sex and Culture, Unwin, 470.

Black Hills, Taylor, 278.
Bloom, W., Histology, 71.
Body, the Human, Martin, 471.
Bouthillon, L., Electricity, 76.
Bowen, N. L., System, MgO-FeO, SiO_2, 151.
Brachiopod, ordovician oligonhynchia, Cooper, 48.
Brachiopoda, Mesozoic, Muir-Wood, 65.
Brachiopods, lower Carboniferous, Belgium, Demanet, 66.
Bridgman, P. W., Metals, Thermodynamics of Electrical Phenomena, 218.
British Columbia, Russell, 54.
Brownmiller, L. T., lime-potash-alumina, 260.
Bruggencate, von P., Astronomy and Astrophics, 223.
Bruner, H. B., World Around Us, 61.
Bugge, A., et al., Norway, Geology of Southern, 386.
Buller, A. H. R., Fungi, 389.
Butler, J. A. V., Thermodynamics, 306.

C

California, Evans, and Williams, 441.
—Woodring, 292.
Campbell, C. D., mylonites, San Andreas Fault Zone, 473.
Cape Cod, etc., Geography and Geology, Woodworth and Wigglesworth, 467.
Carbohydrates, Armstrong, E. F., and K. F., 532.
Cephalopods, actinoceroid, Teichert, 1.
Chadwick, G. H., Pocono, 133.

CHEMISTRY AND CHEMICAL WORKS.

- Carbohydrates, Armstrong, E. F., and K. F., 532.
- Chemistry, Spirit of, Findlay, 386.
- Crystals and Polarising Microscope, Hartshorne and Stuart, 532.
- Electrolytes, Falkenhagen, 533.

---

* This Index contains the General Heads: Chemistry and Chemical Works, Geology and Geological Works, Geological Surveys, Minerals, Obituary, Physics and Physical Works, Rocks, Biology and Biological Works, Paleontology and Paleontological Works; under each the titles referring thereto are included.
Initial capitals are in general used for the title of books noticed.

German Deep-Sea Expedition, 1925-27, 59.
Hydrogen and Oxygen, Hinshelwood and Williamson, 58.
Kinetics and Chain Reactions, Semenoff, 465.
Lime-potash-alumina, Brownmiller, 260.
Molecules and Crystals, Fermi, 467.
Quantum Theory, Temple, 58.
Rocks, potash, Terzaghi, 369.
Soil Analysis, Wright, 466.
Spectrophotometry, Absorption, Twyman and Allsop, 61.
Thermodynamics, Bridgman, 218; Butler, 306.

Chimpanzee, Yerkes, 389.
Cobbold, E. S., Rushton, (Shropshire), Cambrian Area, 66.
Colour Science, Ostwald, 63.
Connecticut, pegmatite, Agar, 57.
Cooper, G. A., oligorhynchia, ordovician, brachiopod, 48.
Crystals and Polarising Microscope, Hartshorne and Stuart, 532.

D

Daly, R. D., Ice Age, 306.
Dartmuthia Patten, Robertson, 323.
Davies, A. M., Faunas, Tertiary, 65.
Demanet, F., Brachiopods, lower Carboniferous, Belgium, 66.
De Terra, H., Human Industries, Palaeolithic, Kashmir, 75.
Dolomite, galena, Mississippi Valley, Kay and Atwater, 98.
Dryden, L., heavy mineral suites, 393.
Dunbrook, R. F., Rubber, 468.

E

Earth, Radio and the Stars, Stetson, 223.
Electricity, Bouthillon and Goudonnet, 76.
Electrolytes, Falkenhagen, 533.
Elias, M. K., grasses, Tertiary, No. America, 24.
English-French Technical Dictionary, Malgorn, 390.
English, G. L., Minerals, 388.
Ethnology, Bureau of, Forty-eighth Annual Report, 1930-31, 76.
Evans, R. D., lavas, radium content of, Calif., 441.
Everyman, Biology for, Thomson, 539.
Evolution, Morgan, 468.

F

Falkenhagen, H., Electrolytes, 533.
Faunas, Miocene and Pliocene mammalian, Nebraska, Stirton and McGrew, 125.
—Tertiary, Davies, 65.
Fermi, E., Molecules and Crystals, 467.
Field, R., stream carved slopes in desert mountains, 313.
Findlay, A., Chemistry, 386.
Flaws and tear faults, Perry, 112.
Flint, R. F., Physical Geology, 220; Pleistocene, Climates of, 381.
Fog, McAdie, 78.
Food and Health, Sherman, 389.
Fossils, Marine Pleistocene Terraces, Calif., Woodring, 292.
Föyn, E., radium, 253.
Freundlich, E. F., Astronomy and Astrophics, 223.
Fungi, Buller, 389.

G

Geodesy, Tardi, 63.

GEOLOGY AND GEOLOGICAL WORKS.

Angola, Mouta and O'Donnell, 64.
Applied, Raguin, 536.
Ardnamuchan, Richey, 466.
Cambrian area, Shropshire, Cobbold and Pocock, 66.
Cape Cod, etc., geology, Woodworth and Wigglesworth, 467.
Cephalopods, actinoceroid, Teichert, 1.
Deposits, arkose, S. Mexico, Krynine, 353.
—glacial, Wis., Terminal Moraine, Penn., Leverett, 220.
Dolomite, galena, upper Mississippi Valley, Kay and Atwater, 98.
Faunas, Tertiary, Davies, 65.
Flaws and tear faults, Perry, 112.
Fossils, Marine Pleistocene Terraces, Calif., Woodring, 292.
Geodesy, Tardi, 63.
Geology, applied, Raguin, 536.
—aspects of, Shand, 309.
—Historical, Ver Wiebe, 67.
—Physical, Longwell, Knopf and Flint, 220.
— — Mather and Roy, 68.
Glacial deposits, Pennsylvania, Leverett, 220.

—development, Central New York, Holmes, 41.
Granites, pre-Cambrian, Black Hills, Taylor, 278.
Grasses, Tertiary, High Plains, No. America, Elias, 24.
Gravity Expedition, West Indies, Navy-Princeton, 1932, 535.
Hypothyridina venustula (Hall), Penn., Willard, 93.
Ice Age, Daly, 306.
Keratophyres, Oregon, spilite problem, Gilluly, Part I, 225, Part II, 336.
Kyanite and Vermiculite Deposits, Georgia, Prindle, 535.
Laccoliths, peridotitic, Newfoundland, Ingerson, 422.
Lavas, radium content, Calif., Evans and Williams, 441.
Leptaenakalk, in Dalarna, Isberg, 387.
Manchoukuo, Expedition to, Tokunaga, 388.
Molecules and Crystals, Fermi, 467.
Mountains, desert, stream carved slopes, Field, 313.
Mylonites, San Andreas Fault Zone, Waters and Campbell, 473.
Norway, Geology of So., Holtedahl, Bugge, et al., 386.
Ostracoda, Paleozoic, Bassler and Kellett, 537.
Petroleum, Wrather and Lahee, 67.
—and Historical, Mather and Roy, 68.
Plankton, Paleozoic, No. America, Schuchert, 462.
Pleistocene, climates of, Flint, 381.
Plutonic bodies, Norway, Holtedahl, 504.
Pocono, Chadwick, 133.
Rhomboid ripple mark, Woodford, 518.
Rocks, potash-rich, Terzaghi, 369.
"Roots-of-mountains" concept, Longwell, 81.
Springs and Bethal, Venter, 64.
Striated rock surfaces, Missouri, Wentworth, 364.
System, $MgO\text{-}FeO\text{-}SiO_2$, Bowen and Schairer, 151.
Thrust Sheets, north of Shoshone River, Wyo., Sheets, 144.

German Deep-Sea Expedition, 1925-27, 59.
Gilluly, J., keratophyres and spilite problem, Oregon, Part I, 225, Part II, 336.
Glacial development, Central New York, Holmes, 41.
Gleditsch, E., radium, 253.
Goudonnet, M., Electricity, 76.
Granites, pre-Cambrian, Black Hills, Taylor, 278.
Grasses, Tertiary, High Plains, No. America, Elias, 24.
Gravity Expedition, West Indies, the Navy-Princeton, 1932, 535.
Grotian, W., Astronomy and Astrophics, 223.

H

Haas, A., Physics, 386.
Haldane, J. S., Biologist, Philosophy of, 468.
Hartshorne, N. H., Crystals and Polarising Microscope, 532.
Hawkes, C., and J., Palaeolithic, Human Industries, Kashmir, 75.
Hess, C. J., Semionotus cf. Gigas, Triassic, Zion Park, Utah, 526.
High Gods, No. America, Schmidt, 72.
Hinshelwood, C. N., Hydrogen and Oxygen, 58.
Histology, Maximow and Bloom, 71.
Hofmann, E., Plants, Fossil, 77.
Holmes, C. D., glacial development, Central New York, 41.
Holtedahl, O., Geology of So. Norway, 386; plutonic bodies, Oslo Region, Norway, 504.
Homoptera, Insects, Osborn, 538.
Hrdlicka, A., anthropoid apes, 34.
Human Industries, Palaeolithic, Kashmir, Hawkes and De Terra, 75.
Hydrogen and Oxygen, Hinshelwood and Williamson, 58.
Hypothyridina venustula (Hall) Penn., Willard, 93.

I

Ice Age, Daly, 306.
Ingerson, E., peridotitic, laccoliths, Newfoundland, 422.
Isberg, O., Leptaenakalk, Dalarna, 387.

J

Jeans, J., Through Space and Time, 470.
Jones, H. S., Astronomy, 310.
Joselin, E. L., Ventilation, 222.

K

Kay, G. M., Galena dolomite, Mississippi Valley, 98.
Kellett, B., Ostracoda, Paleozoic, 537.
Keratophyres, Oregon, Gilluly, Part I, 225, Part II, 336.
Kienle, H., Astronomy and Astrophics, 223.
Kinetics, Chemical, Semenoff, 465.
Knopf, A., Physical Geology, 220.
Kopff, A., Astronomy and Astrophics, 223.
Kriszat, G., Organisms, invisible, 74.
Krynine, P. D., arkose deposits, Mexico, 353.
Kudo, R. R., Protozoan Parasites of Fishes, Illinois, 75.
Kyanite and Vermiculite Deposits, Georgia, Prindle, 535.

L

Laccoliths, peridotitic, Newfoundland, Ingerson, 422.
Lahee, F. H., Petroleum, geology of, 67.
Lassen Volcanic National Park, Calif., 441.
Lavas, radium content of, Calif., Evans and Williams, 441.
Lemon, H. B., Cosmic Rays, 534.
Leptaenakalk, in Dalarna, Isberg, 387.
Leverett, F., Glacial Deposits, Penn., 220.
Lewis, J. A., Physical Science, 63.
Lime-potash-alumina, Brownmiller, 260.
Longwell, C. R., Physical Geology, 220; "Roots-of-Mountains," concept, 81.

Mc

MacBride, T. H., Myxomycetes, 70.
MacCurdy, G. G., Prehistoric Research, 72.
Macfayden, W. A., et al., Paleontology, Mesozoic, British Somaliland, 537.
McAdie, A., Fog, 78.
McCorkle, P., Physical Science, 63.
McGrew, P. O., faunas, Miocene and Pliocene mammalian, Nebraska, 125.

M

Malgorn, G., English-French, Technical Dictionary, 390.
Mammal, middle Eocene, British Columbia, Russell, 54.
Manchoukuo, Expedition to, Tokunaga, 388.
Martin, G. W., Myxomycetes, 70.
—H. N., Human Body, 471.
Mason, F., Order and Intelligence in Nature, 309.
Massa, F., Acoustics, 76.
Mather, K. F., Geology, 68.
Maximow, A. A., Histology, 71.
Maya Village, Redfield and Villa, 222.
Metals, Thermodynamics of Electrical Phenomena, Bridgman, 218.
Mexico, Krynine, 353.
Mineral, facies in metamorphic rocks, Turner, 409.
—Suites, Dryden, 393.
Minerals, English, 388.
—U. S. Bureau of, 68.

MINERALS.
  Broeggerite, Norway, 253.
  Cleveite, Norway, 253.
  Kyanite, Georgia, 535.
  Pegmatite, Connecticut, 56.
  Vermiculite, Georgia, 535.
Molecules and Crystals, Fermi, 467.
Morgan, T. H., Evolution, 468.
Morris, V. N., Rubber, 468.
Mountains, desert, stream carved slopes, Field, 313.
Mouta, F., Angola, geology, 64.
Muir-Wood, H. M., Brachiopoda, Mesozoic, 65.
Mylonites, San Andreas Fault Zone, Waters and Campbell, 473.
Myxomycetes, MacBride and Martin, 70.

N

Namias, J., Atmosphere, Subsidence within the, 538.
National Physical Laboratory—Report for 1833, 218.
Nature, order and intelligence, Mason, 309.
Nebraska, faunas, Stirton and McGrew, 125.
Neuner, E. F., World Around Us, 61.

Newfoundland, Ingerson, 422.
New York, Holmes, 41.
Norway, Holtedahl, 504.
—Geology of So., Holtedahl, Bugge, et al., 386.

OBITUARY.
  Armstrong, L., 391. Arnold, J. L., 542.
  Baker, H. B., 542. Belopolsky, A. A., 391. Brauner, B., 471. Brown, N. E., 224. Burdette, R. C., 311. Buxton, B. H., 311.
  Carney, F., 79. Chewolson, O. D., 391. Clapp, C. M., 311. Cleland, H. F., 311. Cobb, C., 79. Cooke, A. H., 224.
  Day, J. E., 542. De Sitter, W., 79, Dixey, F. A., 391. Dixon, R. B., 311. Duane, W., 391.
  Ewing, J. A., 311.
  Foye, W. G., 311. Fraser, J., 471.
  Graham, M., 391. Griffiths, D., 542. Guthrie, J. E., 542.
  Hantzsch, A., 542. Herrick, W. H., 391. Herzog, R. O., 542. Hodgkinson, W. R., 542. Hopkins, T. C., 472. Hülsen, C., 472.
  Ishikawa, C., 311.
  Jenkins, P. P., 224. Johnson, E. G., 472.
  Lamb, H., 79. Linde von., K., 224. Longstaff, J., 391.
  MacLeod, J. J. R., 472. Mann, A., 312. Mathews, J. A., 391. Morgan, J. L. R., 542. Morris, W., 542. Mulliken, S. P., 224.
  O'Harra, C. C., 392.
  Paterno, E., 542. Porter, D., 392. Pupin, M. I., 540.
  Robertson, R. A., 542. Rowley, R. R., 392.
  Sharpey-Schafer, E., 472. Sinclair, W. J., 472. Smith, T., 312.
  Thomson, R., 392.
  Wallen, A., 472. Weld, H., 542. White, D., 390.

O

Observatory Publications, 77.
O'Donnell, H., Angola, geology, 64.
Oeselaspis, new, Robertson, 453.
Olsen, H. F., Acoustics, 76.
Oregon, E., Gilluly, Part I, 225, Part II, 336.
Organisms, invisible, Uexküll and Kriszat, 74.
Osborn, H., Homoptera, Insects, 538.
Ostracoda, Paleozoic, Index, Bassler and Kellett, 537.
Ostwald, W., Colour Science, 63.

PALEONTOLOGY AND PALEONTOLOGICAL WORKS.
  Apes, anthropoid, Hrdlicka, 34.
  Brachiopoda, Mesozoic, Muir-Wood, 65.
  Brachiopod, ordovician oligorhynchia, Cooper, 48.
  Brachiopods, lower Carboniferous, Belgium, Demanet, 66.
  Dartmuthia Patten, Robertson, 323.
  Faunas, Valentine, Neb., Stirton and McGrew, 125.
  Fossils, Marine Pleistocene Terraces, Calif., Woodring, 292.
  Mammal, middle Eocene, British Columbia, Russell, 54.
  Mesozoic, British Somaliland, Macfayden, et al., 537.
  Oeselaspis, new genus of Ostracoderm, Robertson, 453.
  Semionotus cf. Gigas, Triassic, Utah, Hess, 526.

P

Parasites of Fishes, Protozoan, Illinois, Kudo, 75.
Pennsylvania, glacial deposits, Leverett, 220.
—hypothyridina venustula (Hall), Willard, 93.
Perry, E. L., Flaws and tear faults, 112.
Petroleum, Geology, Wrather and Lahee, 67.
Physical and Historical Geology, Mather and Roy, 68.
—Geology, Longwell, Knopf and Flint, 220.
—Science, McCorkle and Lewis, 63.

PHYSICS AND PHYSICAL WORKS.
  Atom, Mystery of, Wilson, 62.
  Colour Science, Ostwald, 63.
  Metals, the Thermodynamics of Electrical Phenomena, Bridgman, 218.
  National Physical Laboratory—Report for the Year 1933, 218.

Physics, Haas, 386.
  Physics and Mathematics, 62.
  Rays, Cosmic, Lemon, 534.
  System, MgO-FeO-SiO$_2$, Bowen and Schairer, 151.
  World Around Us, Powers, Neuner and Bruner, 61.
Planetarium, Andrissi and Tosi, 539.
Plankton, Paleozoic, No. America, Schuchert, 462.
Plants, Fossil, Hofmann, 77.
Pleistocene, climates of, Flint, 381.
Plutonic bodies, Oslo Region, Norway, Holtedahl, 504.
Pocock, R. W., Shropshire, Cambrian Area, 66.
Pocono, Chadwick, 133.
Potash-rich rocks, Terzaghi, 369.
Powers, S. R., World Around Us, 61.
Pratt, H. S., Animals, a Manual of the Common Invertebrate, 540.
Preston, J. R., Ventilation, 222.
Prindle, L. M., Kyanite and Vermiculite Deposits, Georgia, 535.
Pupin, Michael Idvorsky, Scott, 540.

Q

Quantum Theory, Temple, 58.

R

Radium, Gleditsch and Föyn, 253.
Raguin, E., Geology, 536.
Rays, Cosmic, Lemon, 534.
Redfield, R., Chan Kom, 222.
Research Prehistoric, Amer. School, 72.
Rhomboid ripple mark, Woodford, 518.
Richey, J. E., Ardnamuchan, 446.
Robertson, G. M., Dartmuthia Patten, 323; Oeselaspis, new, 453.

ROCKS.
  Granites, pre-Cambrian, Black Hills, Taylor, 278.
  Metamorphic, mineral facies in, Turner, 409.
  Potash-rich, Terzaghi, 369.
  Striated surfaces, Missouri, Wentworth, 364.
Rodolico, N., Biology, 468.
"Roots-of-Mountains" concept, Longwell, 81.
Roy, C. J., Geology, 68.
Royal Astronomical Society, 538.
Rubber, Science of, Dunbrook and Morris, 468.
Rushton, (Shropshire), Cambrian Area, Cobbold and Pocock, 66.
Russell, L. S., mammal, mid-Eocene, British Columbia, 54.

S

Schairer, J. F., System MgO-FeO-SiO$_2$, 151.
Schmidt, W., High Gods, No. America, 72.
Schuchert, C., Plankton, Paleozoic, No. America, 462.
Science Advisory Board, Report, 1933, 1934, 310.
Scott, C. F., Pupin, M. I., 540.
Semenoff, N., Kinetics and Chain Reactions, 465.
Semionotus cf. Gigas, Triassic, Utah, Hess, 526.
Sex and Culture, Unwin, 470.
Shand, S. J., Geology, 309.
Sheets, M. M., Thrust Sheets, Wyo., 144.
Sherman, H. C., Food and Health, 389.
Soil Analysis, Wright, 466.
Spectrophotometry, Twyman and Allsop, 61.
Springs and Bethal, Geology, Venter, 64.
Stetson, H. T., Earth, Radio and the Stars, 223.
Stirton, R. A., **Faunas,** mammalian, Nebraska, 125.
Striated rock surfaces, Missouri, Wentworth, 364.
Stuart, A., Crystals and Polarising Microscope, 532.
Suites, heavy mineral, Dryden, 393.
System, MgO-FeO-SiO$_2$, Bowen and Schairer, 151.

T

Tardi, P., Geodesy, 63.
Taylor, G. L., granites, pre-Cambrian, Black Hills, 278.
Technical Dictionary, English-French, 390.
Teichert, C., cephalopods, actinoceroid, 1.
Temple, G., Quantum Theory, 58.
Terzaghi, R. D., rocks, potash-rich, 369.
Thermodynamics, Bridgman, 218; Butler, 306.
Thomson, J. A., Biology, 539.
Thrust Sheets, Wyo., Sheets, 144.

e, Through Space and, Jeans, 0.
kunaga, S., Manchoukuo, 388.
ortugas Laboratory, Carnegie Institution, Washington, 7
Tosi, A., Planetarium, 539.
Turner, F. J., metamorphic rocks, mineral facies, 409.
Twyman, F., Spectrophotometry, 61.

U

Uexküll, von. J. v., Organisms, invisible, 74.
Unwin, J. D., Sex and Culture, 470.
Utah, Hess, 526.

V

Van Deman, E. B., Aqueducts, Roman, 69.
Venter, F. A., Springs and Bethal, 64.
Ventilation, Joselin and Preston, 222.
Ver Wiebe, W. A., Historical Geology, 67.
Villa, A., Chan Kom, 222.

W

Waters, A. C., mylonites, San Andreas Fault Zone, 473.
Wentworth, C. K., striated rock surfaces, Missouri, 364.
White, David, obituary, Berry, 390.
Wigglesworth, E., Cape Cod, etc., Geology, 467.
Willard, B., hypothyridina venustula (Hall), Penn., 93.
Williams, H., lavas, radium content of, Calif., 441.
Williamson, A. T., Hydrogen and Oxygen, 58.
Wilson, H. A., Atom, 62.
Wolf, B., Animals, Caves, 75.
Woodford, A. O., rhomboid ripple mark, 518.
Woodring, W. P., fossils, Marine Pleistocene Terraces, Calif., 292.
Woodworth, J. B., Cape Cod, etc., Geology, 467.
World Around Us, Powers, Neuner and Bruner, 61.
Wrather, W. E., Petroleum, 67.
Wright, C. H., Soil Analysis, 466.
Wyoming, Sheets, 144.

Y

Yerkes, R. M., Multiple Choice Problems, Adaptation of Chimpanzee to, 389.